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INDUCTION LINACS AND FREE ELECTRON LASER AMPLIFIERS

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INDUCTION LINACS AND FREE ELECTRON LASER AMPLIFIERS

Symposium on Lasers and Particle Beams for
Fusion and Strategic Defense

University of Rochester
Rochester, New York

Richard J. Briggs

The purpose of this conference, as I understand it, is to bring together the communities involved in fusion research with those involved in directed energy weapons research. Steve Dean pointed out in his opening remarks that there have actually been many connections in the past between activities in fusion research and directed energy weapons. In fact, the activity that I have been involved with at Livermore is probably one of the prime examples of this. I would like, in this talk, to give some perspectives on how these activities interacted over the years. With the formation of the Strategic Defense Initiative (SDI), which is a rather significant new national endeavor, a sense of history is often important. So let us at the outset go back and look at our roots.

A major component of the controlled fusion program at Livermore back in the early 1970's was a machine called Astron. The purpose of the Astron experiment (shown in Fig. 1) was to generate plasma confinement through magnetic field reversal from a circulating electron ring. Next to the Astron fusion experiment was a buncher ring in which the electron beam from the Astron accelerator went around in a circle and over into a 60-foot propagation tank next door (Fig. 2). The purpose of the buncher ring was to make a

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chopped electron beam to study beam propagation in air. This was a program called Seesaw, funded by DARPA. It started in the late 1950's, and the original purpose of that research program was to look at ballistic missile defense concepts with particle beams. Incidentally, the building that housed this experimental apparatus is currently the site of the large magnetic mirror experiment, MFTF.

These investigations of field reversed plasma confinement states for magnetic fusion, the basis for Nick Christofilos' Astron concept, and the particle beam weapon research, both involved making new kinds of accelerators for very high beam currents, unprecedented in their day. The idea that was born out of this need was the linear induction accelerator.

The second version of the Astron accelerator is shown in Fig. 3. Its pulsed power was derived from charged coaxial cables feeding power in at the 25 kV level.

An induction machine is basically a one-to-one transformer where the beam acts as the secondary. Its invention was stimulated by the observation that if I want to accelerate very high currents and remain efficient, I need low impedance drivers. So I just take the impedance I get with transmission line cables and feed it directly to the beam using a magnetic material to act as the isolating core. I can then stack them in series in the fashion shown.

The Astron injector, the second version--the first one was in the early 1960's--operated at about 6 MeV and close to a kiloamp for a pulse duration of three-tenths of a microsecond (Fig. 4). It's burst mode capability was required for the injection of electron pulses fast enough to build up the field reversed configuration for magnetic fusion. The burst mode capability on the later machines (ETA and ATA) is for the purpose of studying hole boring in air, namely, a high repetition rate "machine gun" type of output that drills through the air with lethal electron "bullets."

The Advanced Test Accelerator (ATA) is the largest machine in this family. It represents a factor of ten increase both in current and in voltage over the Astron. To make that kind of step in technology, we started out making a smaller machine, the Experimental Test Accelerator (ETA), as a technology test bed. The ATA operated at its full design specifications in approximately a year following the completion of construction.

Figure 5 shows the facility as it was first completed. There is a long tank for propagation studies and a door that can slide back for projecting beams into air to study their propagation. The accelerator is about 70 meters long and the photo in Fig. 6 shows the accelerator looking back towards the injector. The accelerator modules are driven by the black transmission line cables at the 250 kV levels, an order of magnitude bigger voltage per module than the Astron. That was one of the significant steps forward in the pulse power technology in this development.

The high beam currents of ATA push against a very fundamental limit in all linacs, namely, transverse beam breakup instabilities where the beam excites transverse modes in the accelerator structures (Fig. 7). In induction machines, one has a considerable advantage over rf linacs, since the cavities themselves are inherently very low Q structure since the ferrite is a very good microwave absorber. We also went to great lengths to shape the cavities, resulting in Q's less than four for all modes. However, even if we destroy all resonances the very presence of accelerating gaps leads to resistive impedances seen by the beam that will make it unstable. Basically, the problem is that an injected beam is always going to have a little noise on it, a coherent distortion to it, and that distortion will drive fields in the cavity that feed back on the beam and cause growth of the transverse distortions (Fig. 7).

That problem, in fact, limited Astron to less than a kiloamp and was a well-recognized obstacle when we started ATA. We were looking for innovative solutions along the way, and we ended up developing a technique called laser guiding (Fig. 8).

In this technique, a small diameter KrF laser beam shoots through the entire accelerator (and another 30 meters beyond). A background of benzene gas photoionizes efficiently with this KrF laser, and we feed this gas in from about the 5 MeV point on down the machine, at a pressure of approximately 10^{-4} Torr. This is a small amount of gas, too little to affect the voltage holding. The net effect is to quiet the beam by orders of magnitude. It basically kills the transverse instability, since the low density column of ions creates focusing forces that are nonlinear enough to introduce a substantial amount of Landau damping or phase mixing. This can kill off these instabilities completely, something that is extremely difficult, if not impossible to do, with conventional magnet focusing.

This is a real breakthrough, a really novel technique, for transport of high current beams through an accelerator that was pioneered by my colleauges at Livermore. An explanation of the underlying principles is diagramed in Fig. 9. The laser beam runs along at the speed of light and the E-beam chases after it at effectively the speed of light, so everything keeps in step with each other. The laser beam leaves a photoionized column behind it. These intense electron beams create megavolt per centimeter E-fields, and that field takes the plasma electrons and pushes them right out of the way leaving a bare ion cloud. With relativistic beams in vacuum, their space charge defocusing is offset by the magnetic pinch fields, so a few ions in the beam can do an adequate job of focusing it.

Many people have read Scientific American articles, I suspect, on why charged particle beams cannot be used in space. Now it is a fairly straightforward extrapolation, already mentioned in Lou Marguet's talk, that if I perturb this laser-focused electron beam with a cross-magnetic field, the beam would ignore it and follow the laser-created ion column, because it is very easy to make the ion restoring forces bigger than a weak deflection magnetic field. So you <u>can</u> shoot electron beams across weak magnetic fields and consider applications of laser-guided beams in near-space environments.

I now turn to the subject of free electron lasers. Following Madey's classic experiment, a group at Livermore started thinking about whether the Free Electron Laser (FEL) might be useful as an advanced driver for Inertial Fusion (ICF). The cartoon in Fig. 10 from those early days is shown here to illustrate our thought process. One has an accelerator and a set of wigglers (the thin lines on this drawing) aimed toward the target chamber in this single-pass amplifier concept. This concept is particularly well suited for induction linacs, although the drawing shows a betatron on it; at the present time, we consider the electron beam brightness requirements for very short wavelength lasers beyond the capability of betatrons.

Induction machine pulse lengths of tens of nanoseconds and their very high peak powers are on the right scale for an ICF driver. This is not something that you can go out and do tomorrow, by any stretch of the imagination, but looking to the more distant future, it is perhaps another common thread between fusion and SDI laser technology developments.

The FEL amplifier concept using induction accelerators is illustrated in Fig. 11. The accelerator can be extremely efficient, better than 50%, particularly with the new magnetic driver technology that I will discuss later. The electron beam goes through the wiggler once and then into a beam dump (where we could use energy recovery systems, but that would be a question of when capital costs of such a system would warrant it).

We use a master oscillator, but since the amplifier gains are greater than 30 or 40 dB per pass, all of the stress involving power and efficiency is put on the free electron laser itself. The optical beam expander shown in Fig. 11 illustrates one of the nice features of the amplifier: you can back away as far as you like for the first optic elements. In particular, some of the more speculative ideas for fusion applications involve using the beam itself to focus the laser onto the pellet so we never come out of vacuum or go through any material lens The figure is drawn for SDI-type applications, however, where one would be using a relay mirror.

The key questions with free electron lasers are <u>not</u> whether the relativistic particles going through an alternating magnetic field will radiate or not. That is known and used routinely in synchrotron light facilities. It is whether you can make it a coherent "laser-like" action, and more than that, whether you can really efficiently convert energy from the electron beam. There are various ideas--storage rings, rf machines with recovery, and so on--to try to get that coherent narrow band radiation and efficiency.

Theoretical studies of our amplifiers indicate that if we get the right electron beam current and brightness, we can get 30 to 40 percent conversion of beam energy into laser light with the tapered wiggler in a single pass. Since the magnetic pulse systems that we have developed are currently in the 50 to 70 percent efficiency, the overall efficiency could, in fact be quite exciting, if real. So, the main issue is the physics of the tapered wiggler based on the ideas of Rosenbluth, Kroll and Morton. In our experimental program we started in the microwave frequency range, since FEL physics is very scalable. We used the 4 MeV ETA machine and selected a kiloamp of beam for a physics test of the tapered wiggler using the electromagnetic wiggler shown in Fig. 12. It has about a 10 cm period and every period can be independently

controlled. Since the machine runs at 1 Hz, it is an excellent physics test bed for verifying codes. If we look at the growth from noise in this experiment at the kiloamp level, we have achieved about 80 dB of gain over three meters (Fig. 13). You do not need much front-end drive with an amplifier like this.

This ETA experiment has produced a very good microwave source, but for strategic defense applications, scaling to short wavelengths is the important issue. To do this in a free electron laser, the first step is to go to higher energy. From FEL scaling laws, at a given wiggler wavelength (like 10 cm), if we go from 5 to 50 MeV we decrease the wavelength by a couple of orders of magnitude (Fig. 14).

In addition, you must have very parallel electron flow which translates into a minimum beam brightness (or space-based density) to get efficient FEL operation at short wavelengths. Finally, we need to go to high average power and our basic program strategy is to go towards short wavelengths and high average power simultaneously in our next generation facilities. We are able to do this because of the dramatic developments in power conditioning systems for induction machines. Magnetic pulse power systems have now been deployed on a little accelerator called the High Brightness Test Stand shown in Fig. 15. To provide shielding in this machine, which has megawatt average power drive capability, instead of using a lot of concrete they put the machine under water. The crew can climb in the machine, work on it, climb out again, and fill it up with water when it runs.

The next major step in our FEL program is an experiment at 10 micron wavelengths on the ATA. After that, progress to visible wavelengths will require machines with even higher voltages, assuming that the physics experiments on ATA verify our basic understanding of high gain FEL amplifiers at optical wavelengths.

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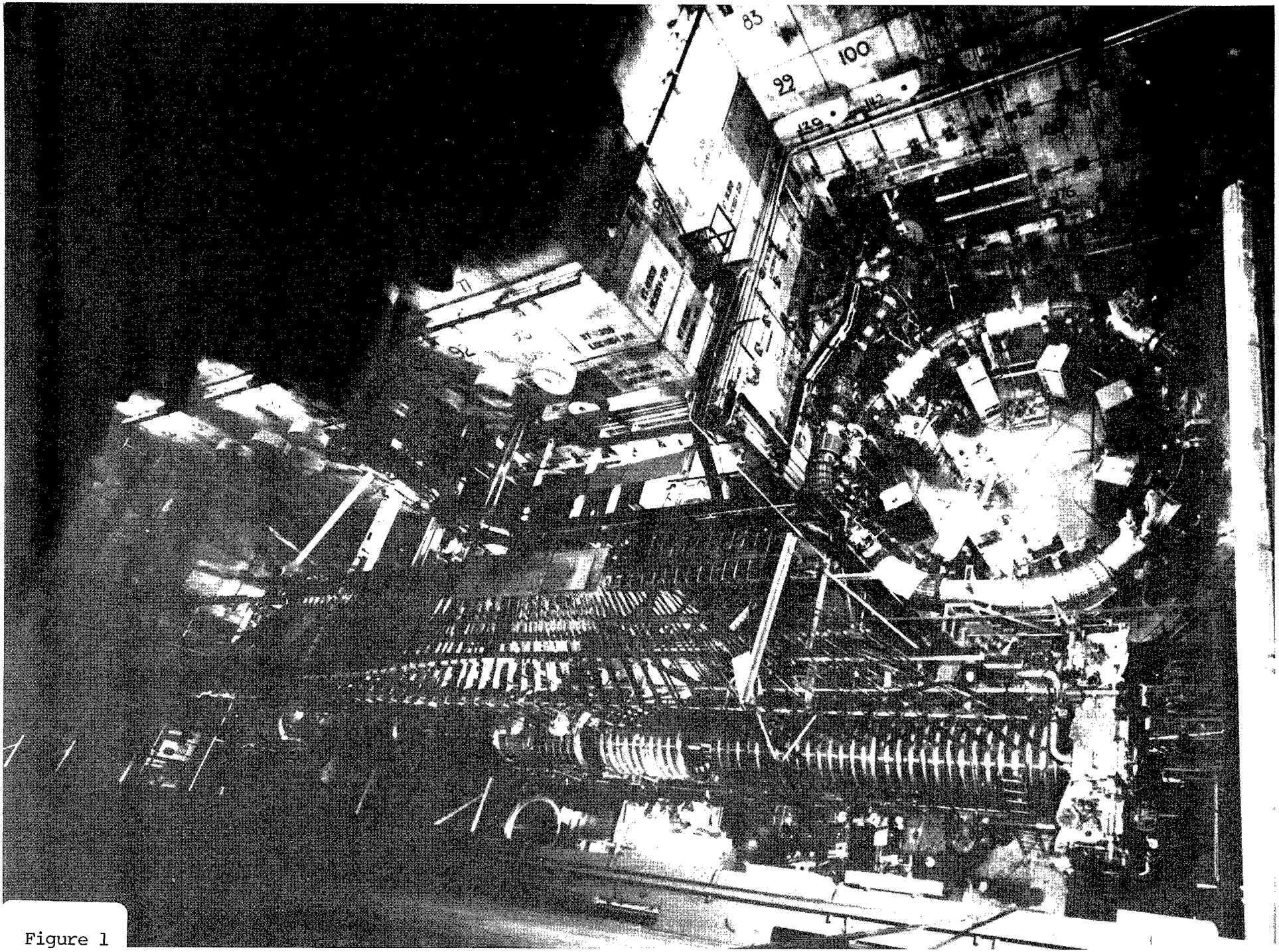


Figure 1

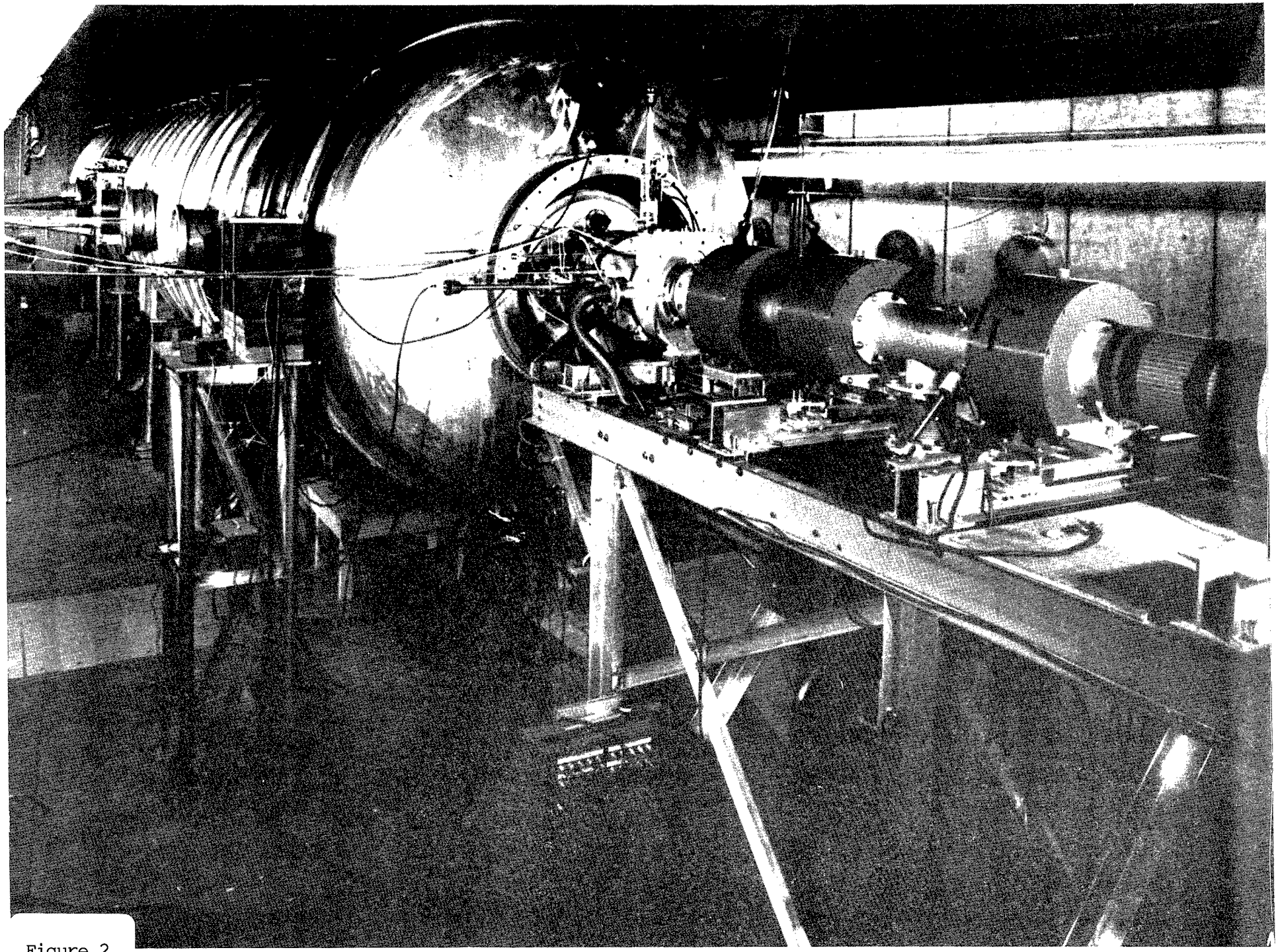


Figure 2

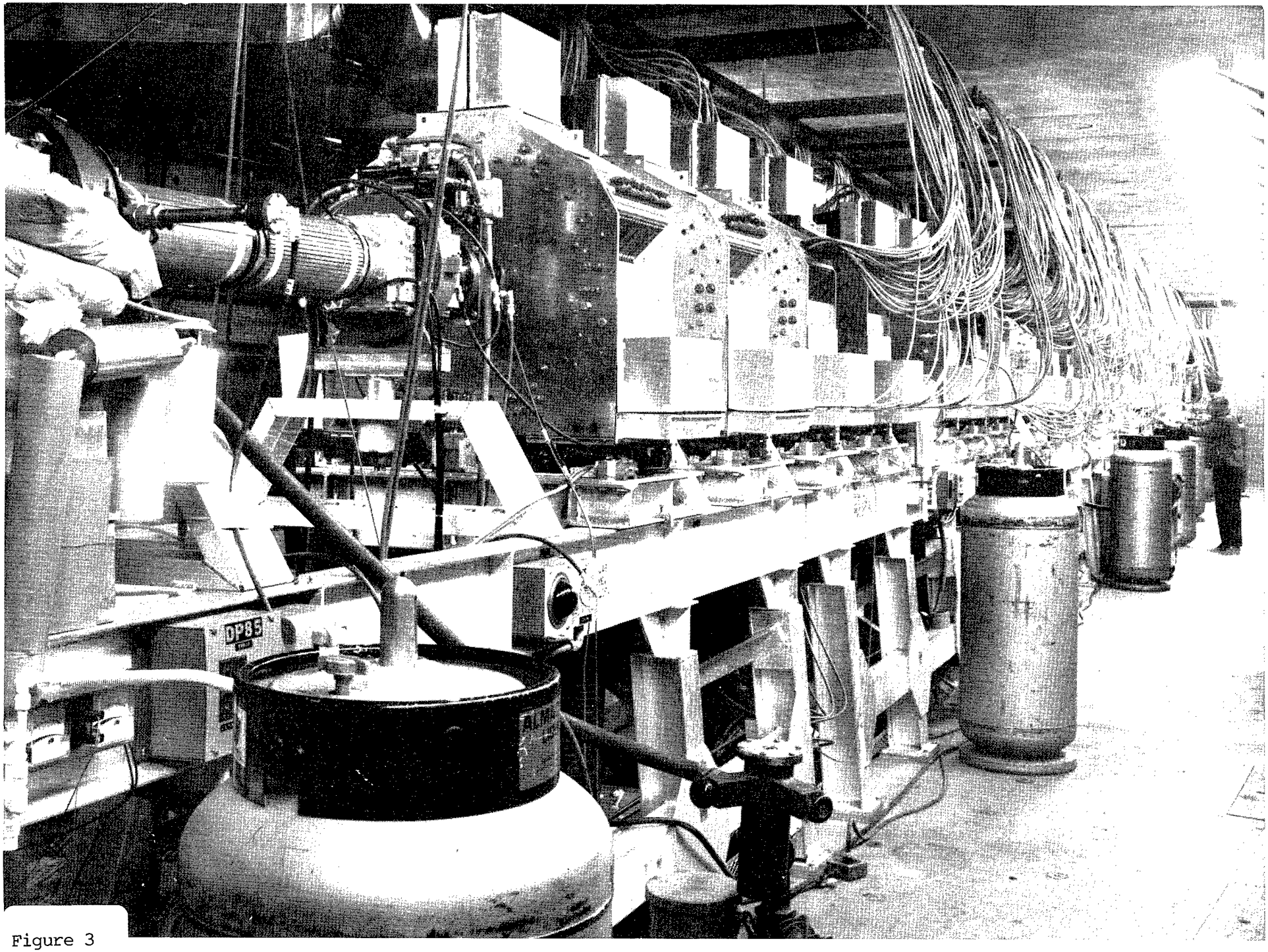


Figure 3

Linear Induction Accelerator

	Kinetic Energy	Beam Current	Pulse Length	Avg. Rep Rate (Max)	Burst Rep. Rate
Astron injector, LLNL (1968)	6 MeV	800 A	300 ns	60 Hz	800 Hz for 100 pulses
ERA injector, LBL (1971)	4 MeV	1,000 A	45 ns	5 Hz	—
NBS prototype (1971)	0.8 MeV	1,000 A	2,000 ns	1 Hz	—
ETA (1979)	4.5 MeV	10,000 A	30 ns	2 Hz	900 Hz for 5 pulses
ATA 1983	50 MeV	10,000 A	60 ns	5 Hz	(1,000 Hz for 10 pulses)

Figure 4

4/85

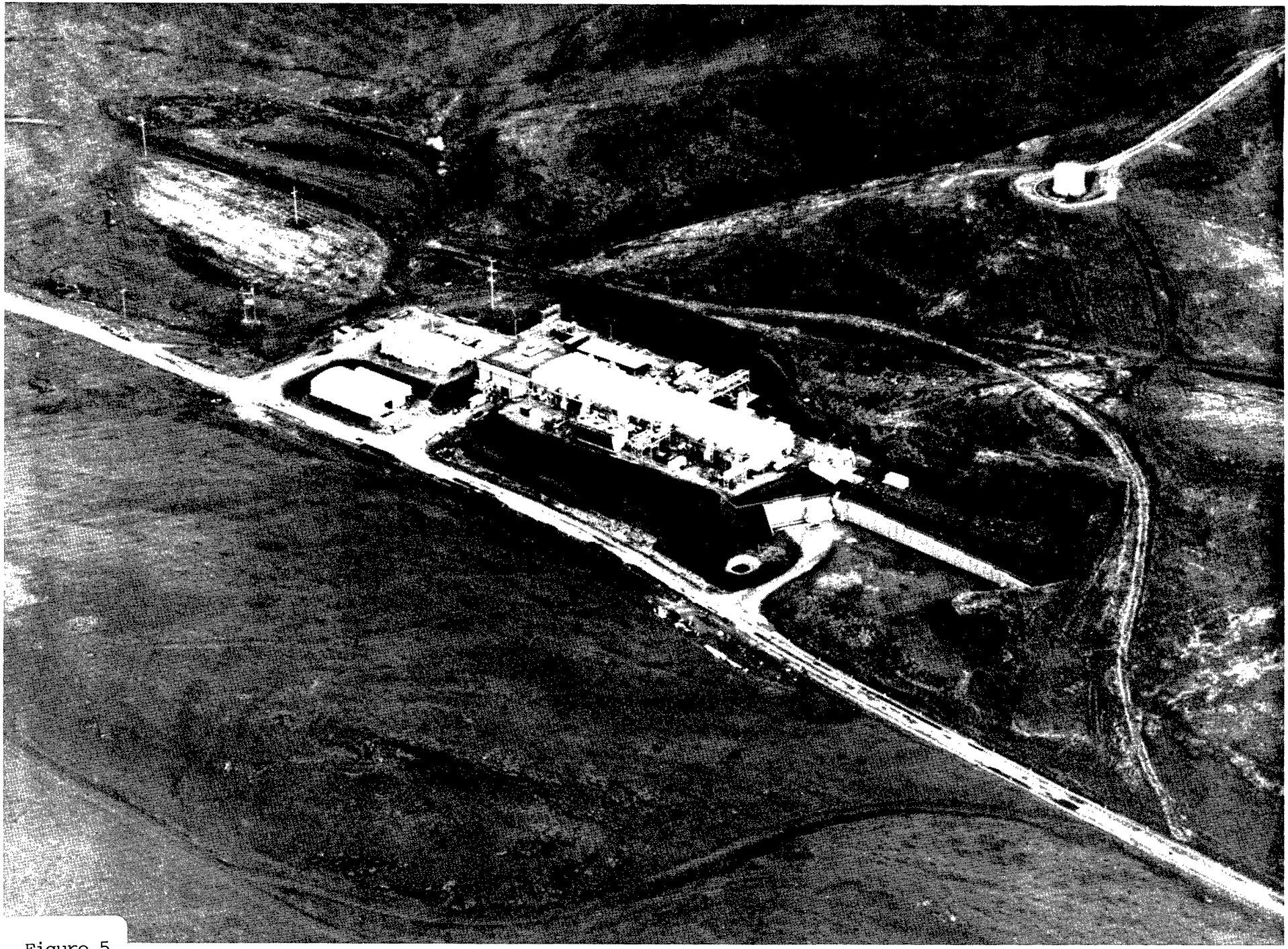


Figure 5

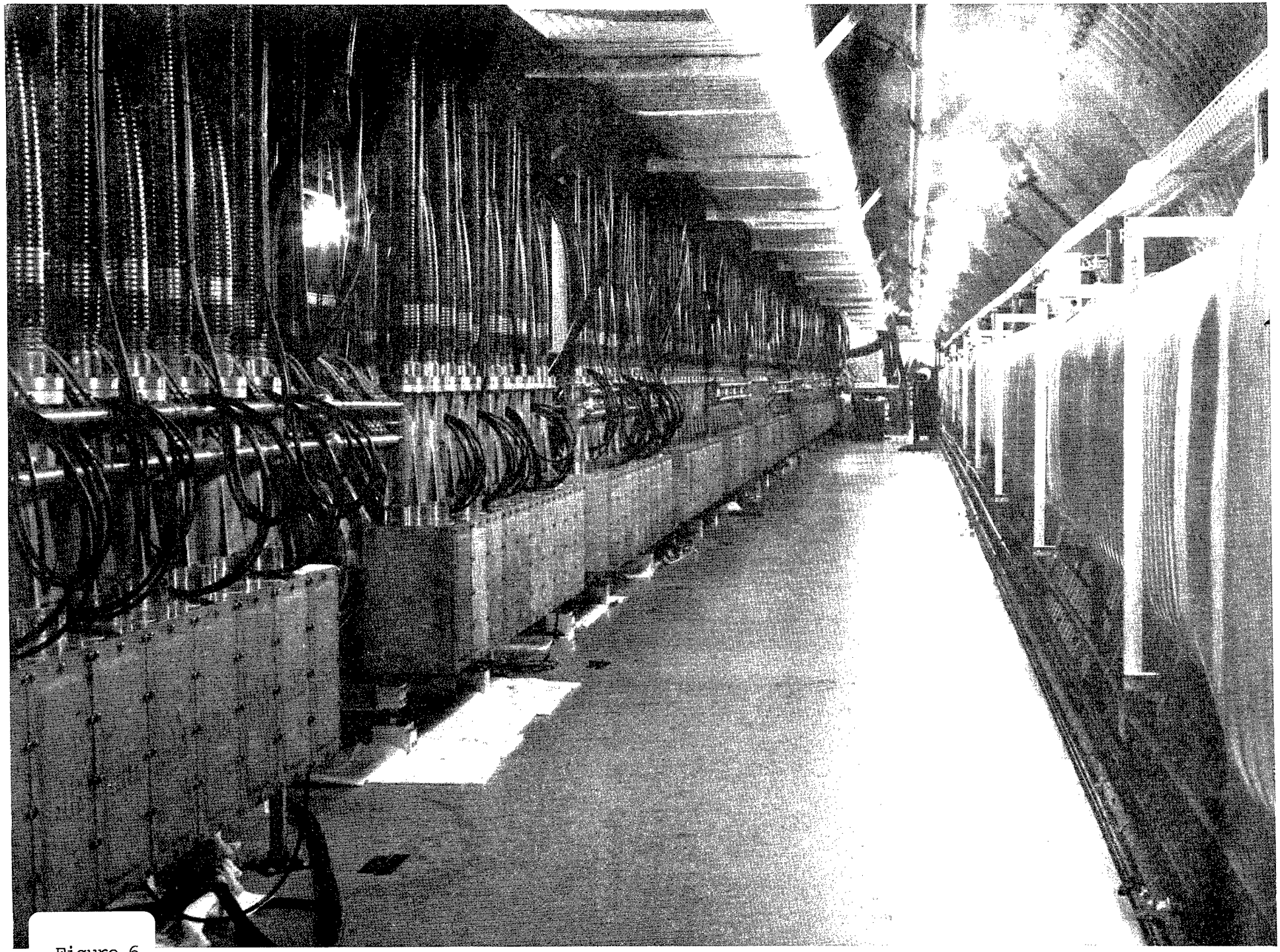


Figure 6

The beam break-up instability

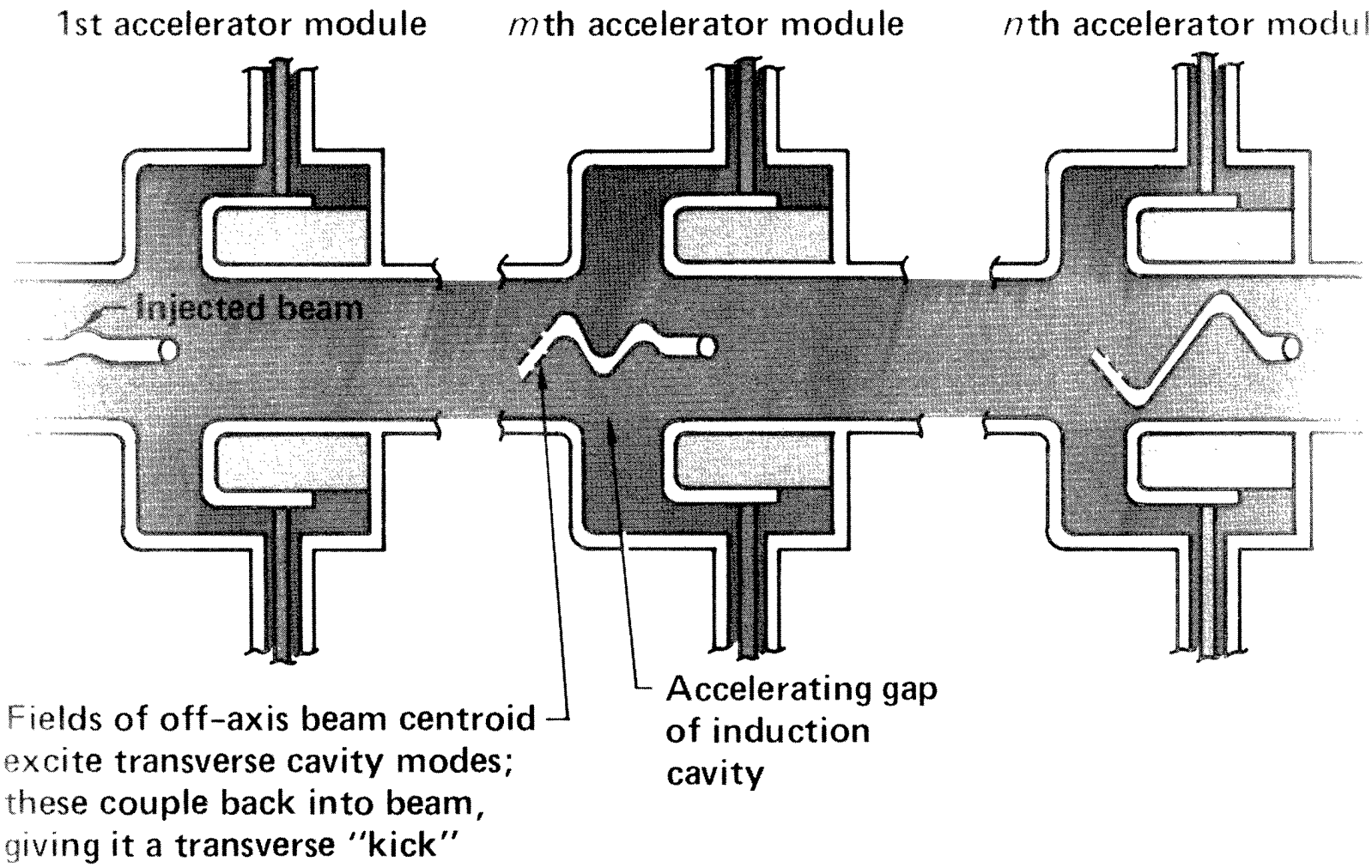


Figure 7

With laser guiding transverse beam motion within ATA is stabilized and suppressed

- Oscilloscope traces on left are from magnetic induction loops at different accelerator locations. Data from one beam pulse is shown in each column. The two columns indicate reproducibility. The oscilloscope trace in the bottom right is accelerator output current (2kA/div. 10 nS/div.).

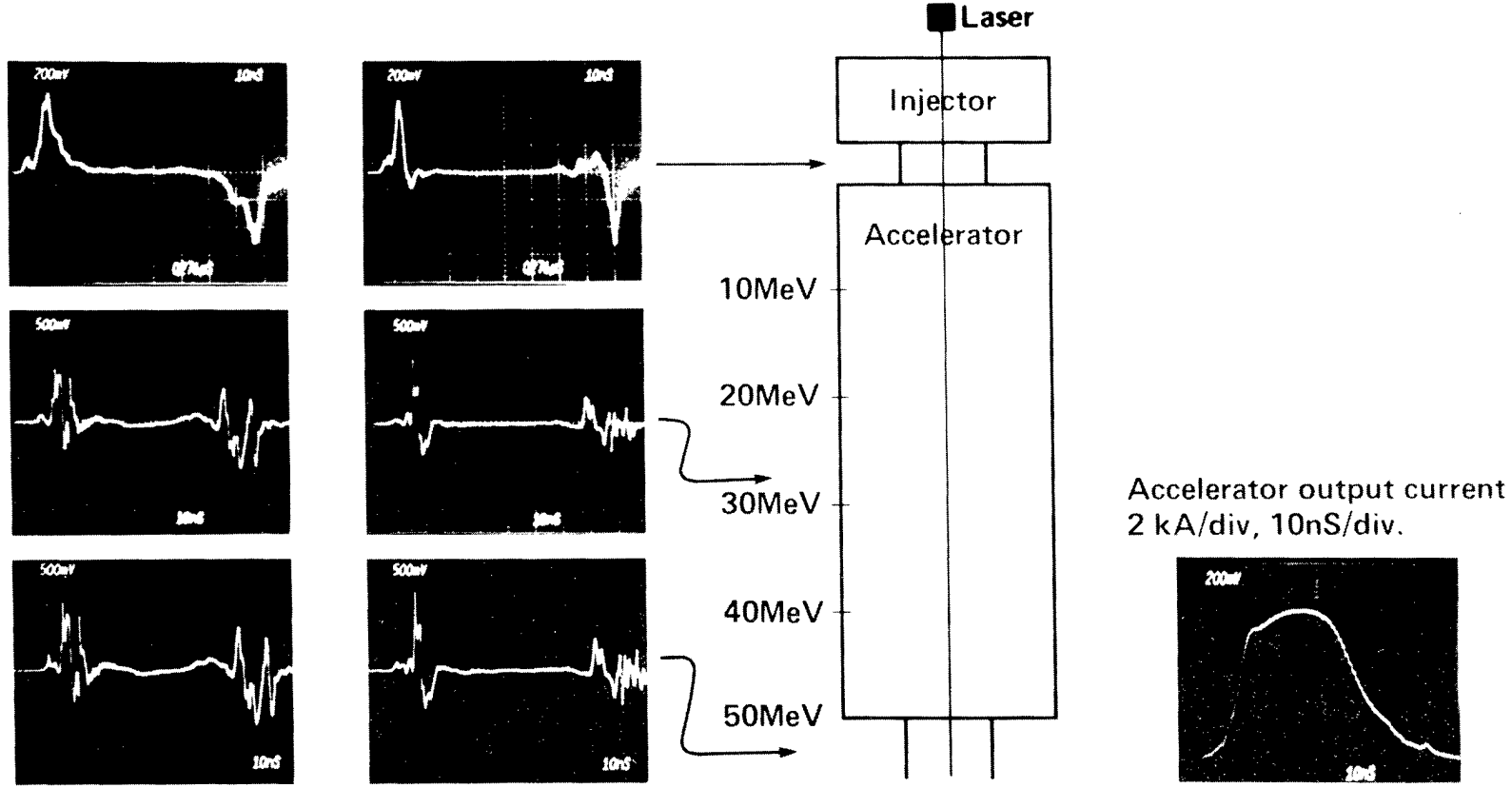
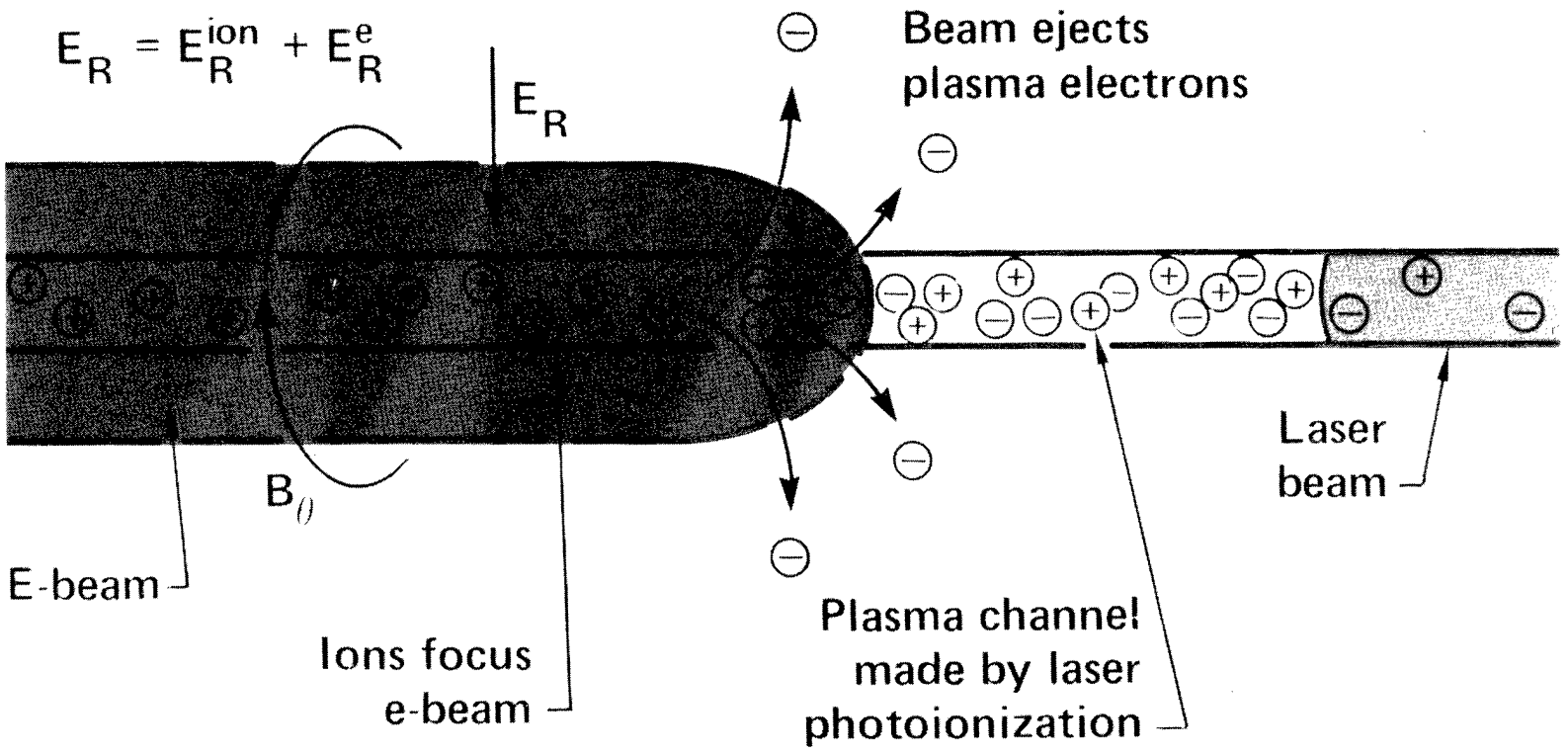


Figure 8

Principles of laser guiding



Net force on beam electrons $F = E_R^{ion} + \underbrace{(E_R^e - v_z B_\theta)}_{\sim 0\ (1/\gamma^2)}$

60 B 0784 49

Figure 9

FREE ELECTRON LASER FUSION DRIVER

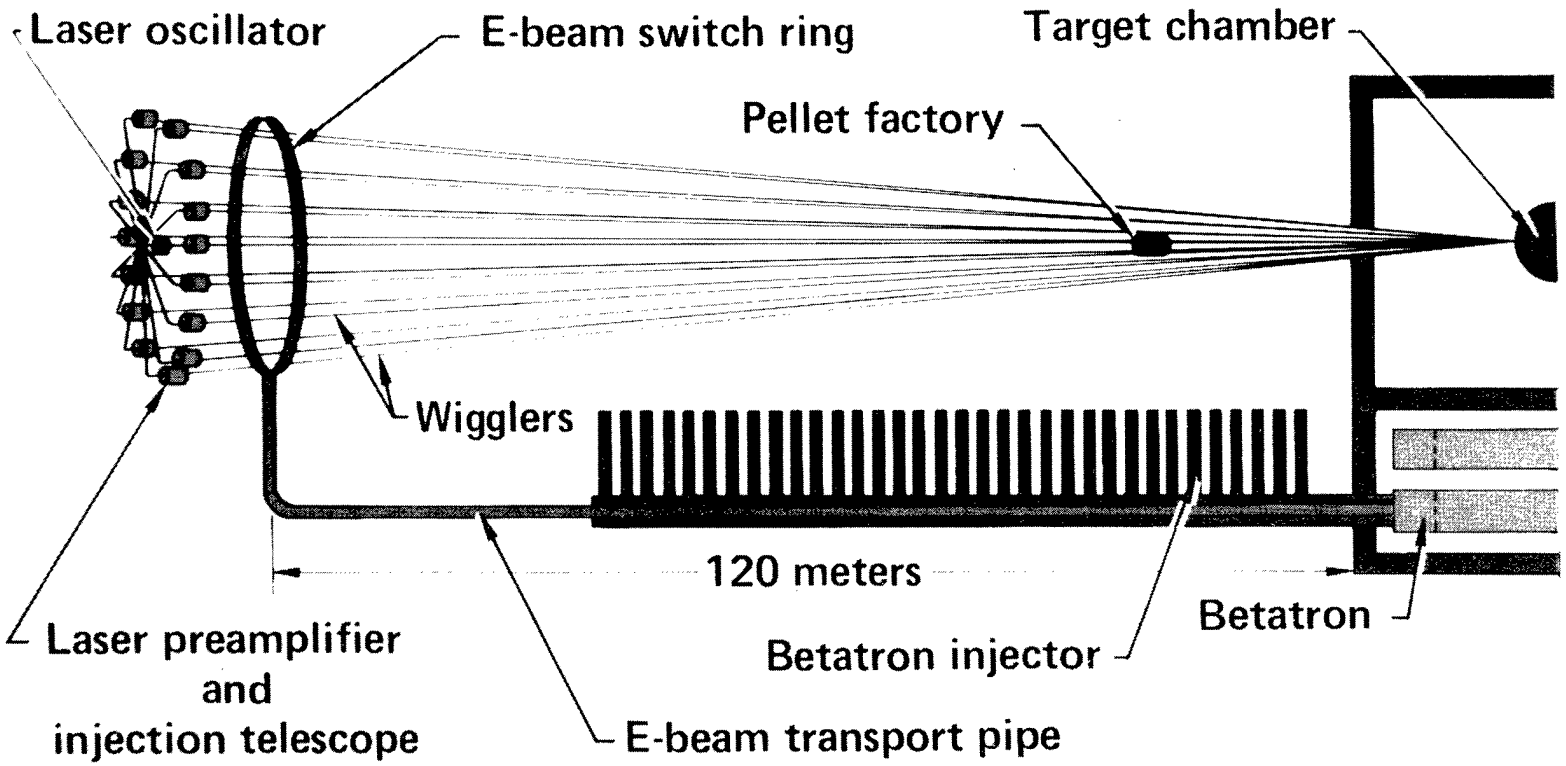


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Figure 10

Component technologies for a high power master-oscillator power amplifier FEL

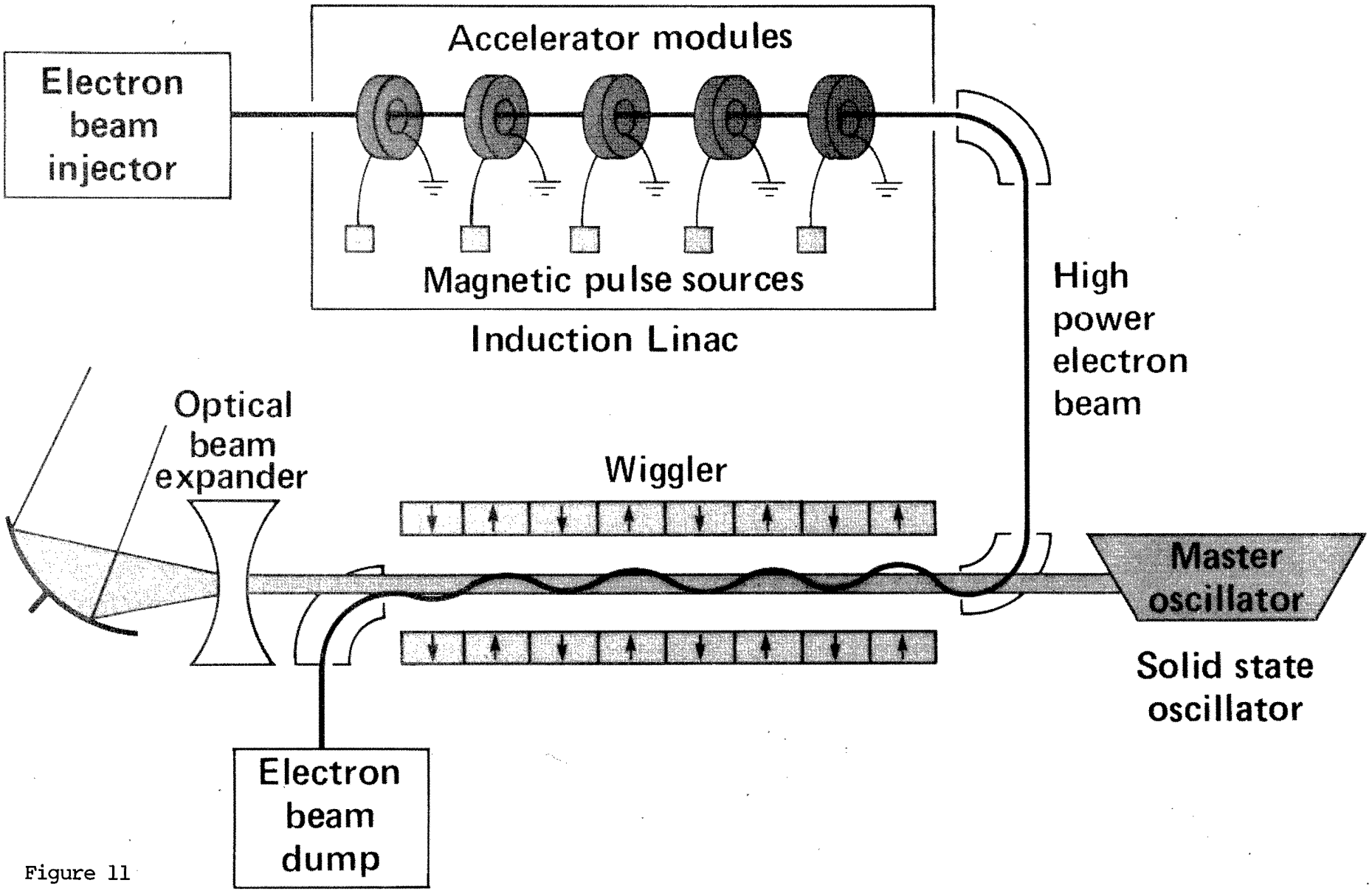

Figure 11

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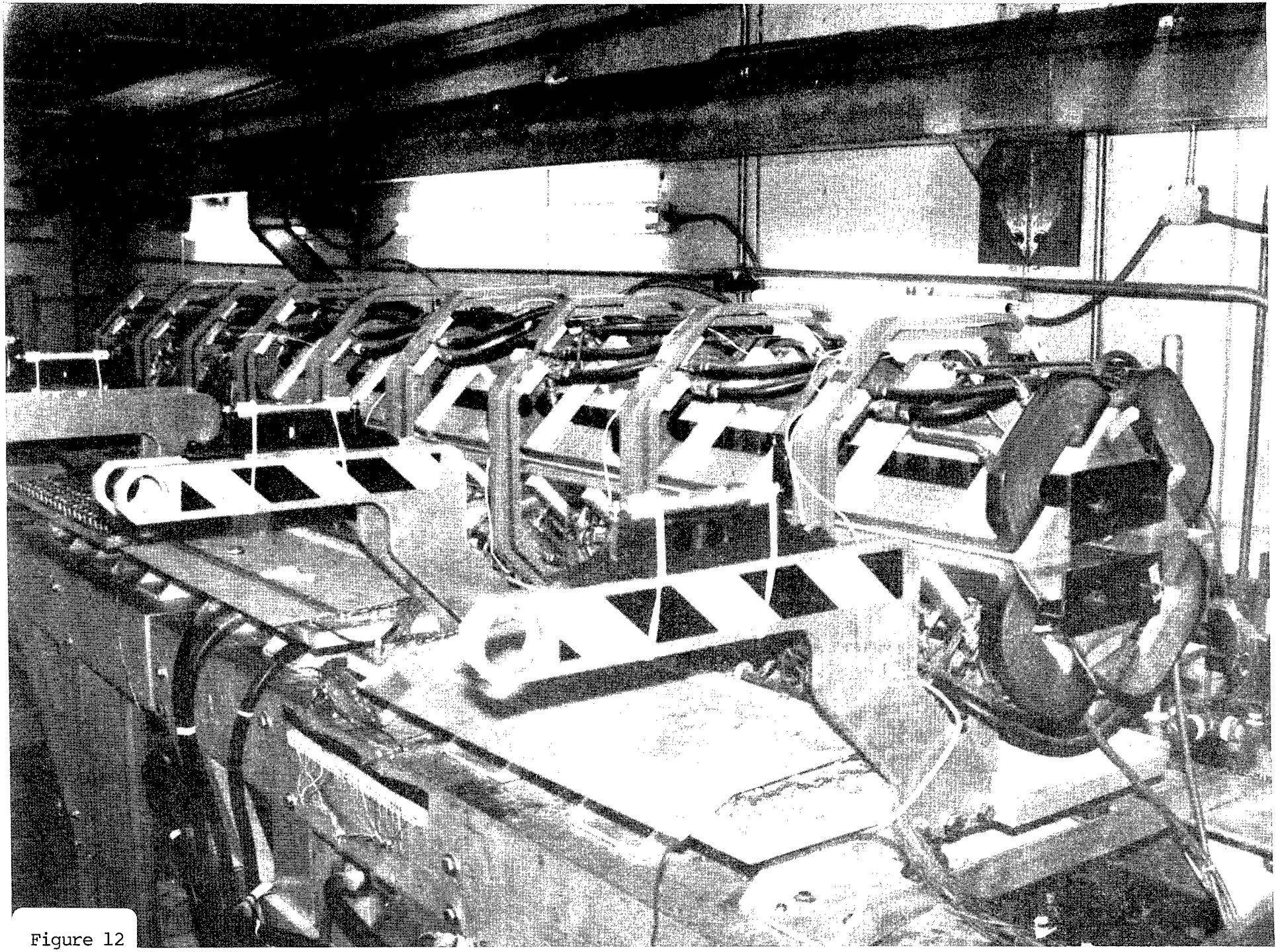


Figure 12

Small signal gain

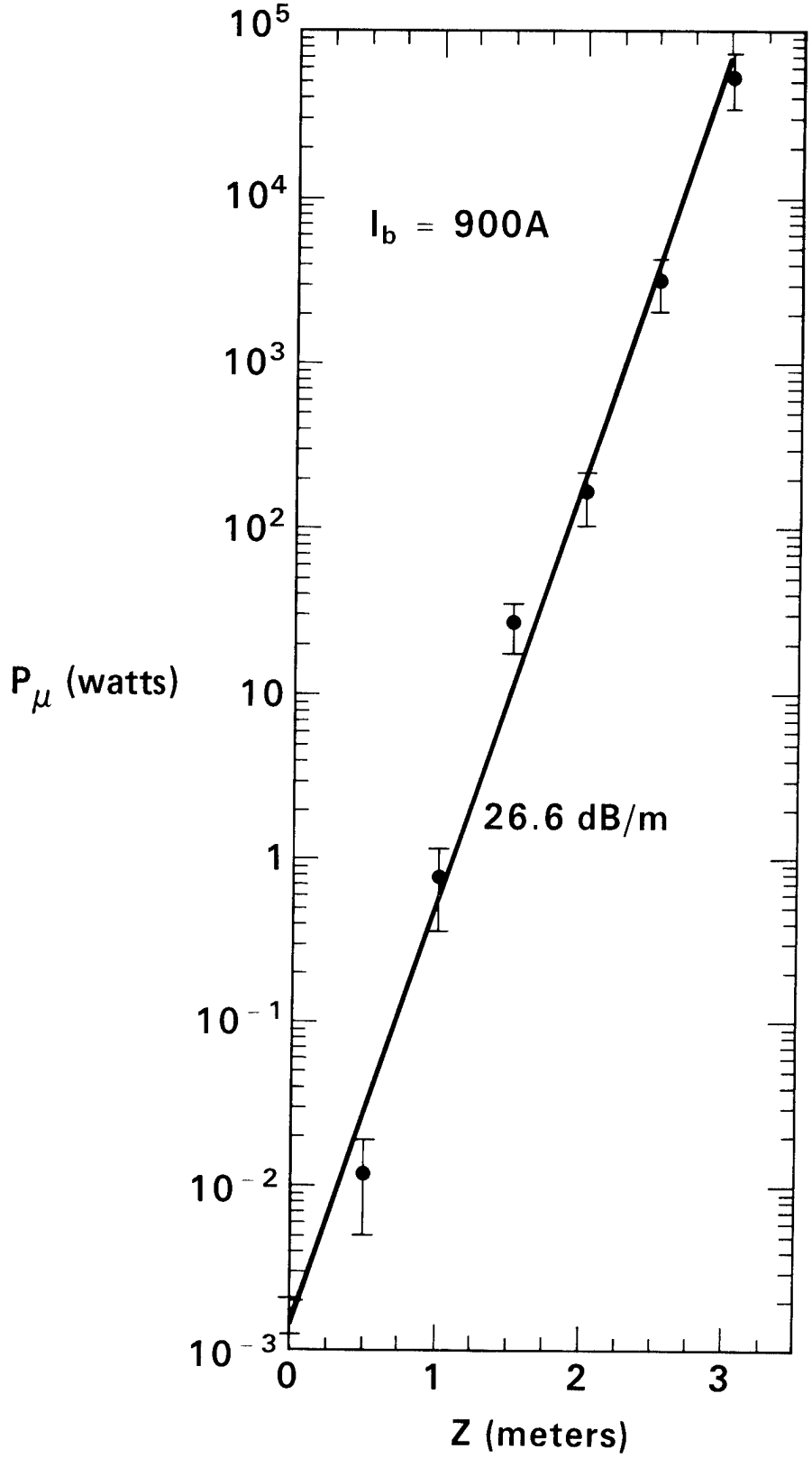


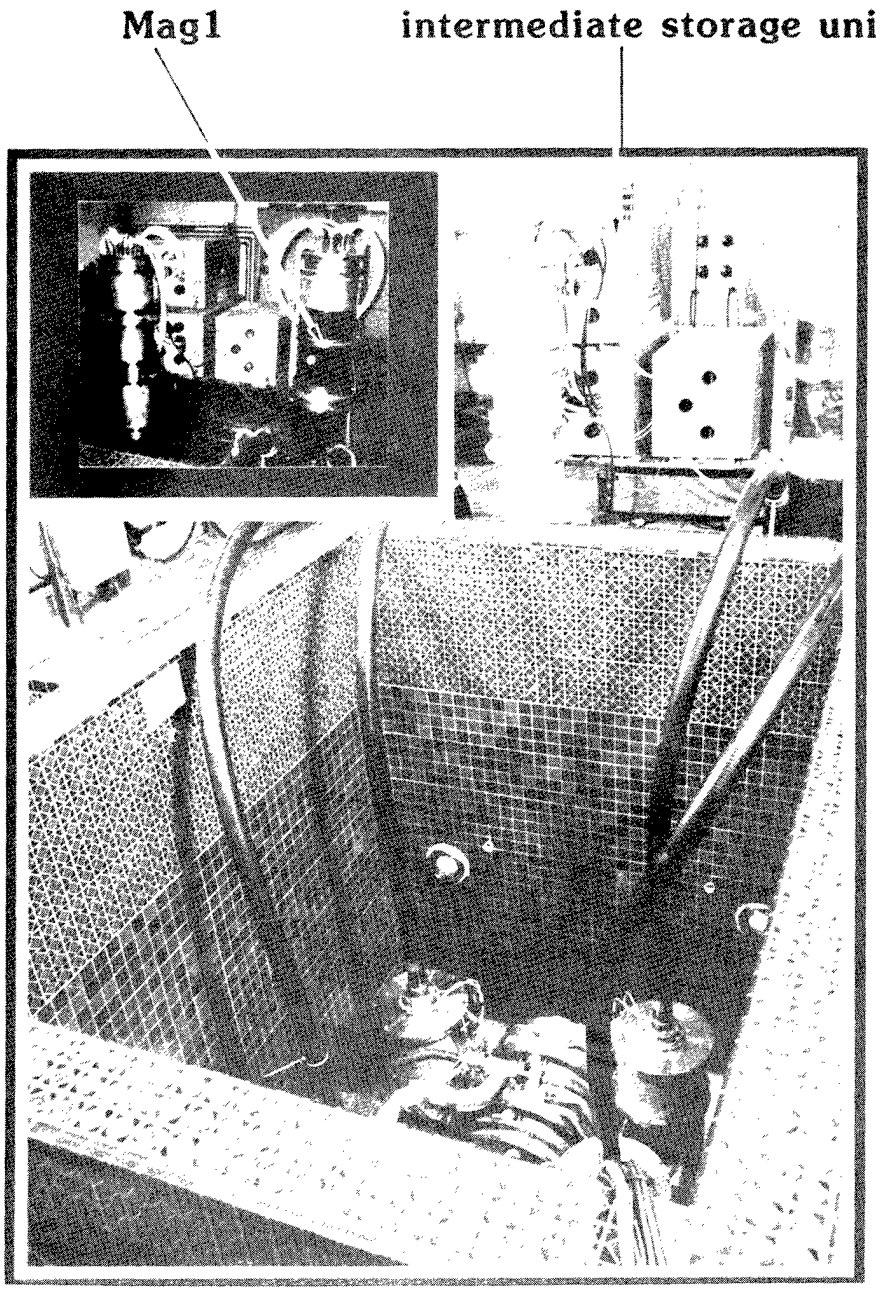
Figure 13

Scaling to short wavelengths and high average powers by

- Increased voltage ($\lambda_s \sim \lambda_w/2\gamma^2$)
- Further improvements in electron beam brightness (emittance)
- Conversion to magnetic modulator power systems

Figure 14

HBTS
HIGH BRIGHTNESS TEST STAND



NONLINEAR MAGNETIC ACCELERATOR DRIVE
2000J/PULSE, $25 \cdot 10^9$ WATTS PEAK

Figure 15

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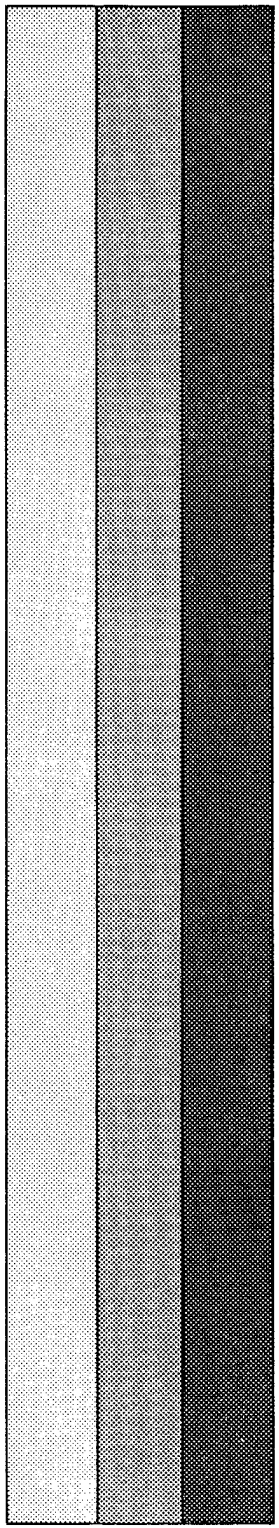

Designation: E 595 - 90

AMERICAN SOCIETY FOR TESTING AND MATERIALS
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If not listed in the current combined index, will appear in the next edition.

Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment[1]

This standard is issued under the fixed designation E 595; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This test method has been approved for use by agencies of the Department of Defense. Consult the DoD Index of Specifications and Standards for the specific year of issue which has been adopted by the Department of Defense.

1. Scope

1.1 This test method covers a screening technique to determine volatile content of materials when exposed to a vacuum environment. Two parameters are measured: total mass loss (TML) and collected volatile condensable materials (CVCM). An additional parameter, the amount of water vapor regained (WVR), can also be obtained after completion of exposures and measurements required for TML and CVCM.

1.2 This test method describes the test apparatus and related operating procedures for evaluating the mass loss of materials being subjected to 125°C at less than 7×10^{-3} Pa (5×10^{-5} torr) for 24 h. The overall mass loss can be classified into noncondensables and condensables. The latter are characterized herein as being capable of condensing on a collector at a temperature of 25°C.

NOTE 1—Unless otherwise noted, the tolerance on 25°C and 125°C is ±1°C and on 23°C is ±2°C. The tolerance on relative humidity is ±5 %.

1.3 Many types of organic, polymeric, and inorganic materials can be tested. These include polymer potting compounds, foams, elastomers, films, tapes, insulations, shrink tubings, adhesives, coatings, fabrics, tie cords, and lubricants. The materials may be tested in the "as-received" condition or prepared for test by various curing specifications.

1.4 This test method is primarily a screening technique for materials and is not necessarily valid for computing actual contamination on a system or component because of differences in configuration, temperatures, and material processing.

1.5 The criteria used for the acceptance and rejection of materials shall be determined by the user and based upon specific component and system requirements. Historically, TML of 1.00 % and CVCM of 0.10 % have been used as screening levels for rejection of spacecraft materials.

1.6 The use of materials that are deemed acceptable in accordance with this test method does not ensure that the system or component will remain uncontaminated. Therefore, subsequent functional, developmental, and qualification tests should be used, as necessary, to ensure that the material's performance is satisfactory.

1.7 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Document

2.1 *ASTM Standard:*
E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods[2]
2.2 *Adjunct:*
Micro VCM Detailed Drawings[4]

3. Terminology

3.1 *Definitions:*

3.1.1 *collected volatile condensable material, CVCM*—the quantity of outgassed matter from a test specimen that condenses on a collector maintained at a specific constant temperature for a specified time. CVCM is expressed as a percentage of the initial specimen mass and is calculated from the condensate mass determined from the difference in mass of the collector plate before and after the test.

3.1.2 *total mass loss, TML*—total mass of material outgassed from a specimen that is maintained at a specified constant temperature and operating pressure for a specified time. TML is calculated from the mass of the specimen as measured before and after the test and is expressed as a percentage of the initial specimen mass.

3.1.3 *water vapor regained, WVR*—the mass of the water vapor regained by the specimen after the optional reconditioning step. WVR is calculated from the differences in the specimen mass determined after the test for TML and CVCM and again after exposure to a 50 % relative humidity atmosphere at 23°C for 24 h. WVR is expressed as a percentage of the initial specimen mass.

4. Summary of Test Method

4.1 This microvolatile condensable system[3] was developed from an earlier system for determination of

[1] This test method is under the jurisdiction of ASTM Committee E-21 on Space Simulation and Applications of Space Technology and is the direct responsibility of Subcommittee E21.05 on Contamination.

Current edition approved Feb. 23, 1990. Published April 1990. Originally published as E 595 - 77. Last previous edition E 595 - 84.

[2] *Annual Book of ASTM Standards*, Vol 14.02.

[3] Muraca, R. F., and [illegible] Outgassing Data for Spacecraft Applications," SRI Project ASD-5046, NASA CR-89557, N67-40270, Stanford Research Institute, September, 1967.

[4] Available from ASTM Headquarters. Order PCN 12-505950-00.

TABLE 1 Test Apparatus Dimensions (See Fig. 2)

Letter	mm	Tolerance	in.	Tolerance	Notes
A[A]	6.3	±0.1	0.250	±0.005	diameter[B]
B[A]	11.1	±0.1	0.438	±0.005	diameter[B]
C[A]	33.0	±0.1	1.300	±0.005	diameter[B]
D[A,C]	13.45	±0.10	0.531	±0.005	
E[A,C]	9.65	±0.10	0.380	±0.005	
F[A,C]	0.65	±0.10	0.026	±0.005	
G[C]	7.1	±0.3	0.50	±0.01	
H[A]	0.75	±0.10	0.030	±0.05	stock size
J[A]	12.7	±0.3	0.500	±0.010	
K	1.6	±0.8	1/16	±1/32	
L	8.0	±0.8	7/16	±1/32	
M	16.0	±0.1	0.625	±0.005	cover plate must fit snugly
N	16.0	±0.8	5/8	±1/32	
P	32.0	±0.8	1 1/4	±1/32	
Q	50.0	±0.8	2	±1/32	
R	25.5	±0.8	1	±1/32	
S	0.4	±0.3	0.015	±0.010	half stock thickness
T	12.0	±0.8	1/2	±1/32	
U	25.5	±0.8	1	±1/32	
V	25.5	±0.8	1	±1/32	
W	50.0	±0.8	2	±1/32	
X	6.0	±0.8	1/4	±1/32	
Y	25.0	±0.8	1	±1/32	
Z	1.6	±0.8	1/16	±1/32	radius, typical

[A] Critical dimensions that must be maintained for test results to be comparable.
[B] Diameters must be concentric to ±0.1 mm (±0.005 in.) for test results to be comparable.
[C] Dimensions include plating thickness. Satisfactory surfaces have been produced by making substrate surface finish, 1.6 µm RMS (63 µin. RMS), highly polished, plated with electroless nickel, 0.0127-mm (0.0005-in.) thick, and finished with electroplated chromium, 0.0051-mm (0.0002-in.) thick.

macrovolatile condensables that required much larger samples and a longer test.

4.2 The test specimen is exposed to 23°C and 50 % relative humidity for 24 h in a preformed, degreased container (boat) that has been weighed. After this exposure, the boat and specimen are weighed and put in one of the specimen compartments in a copper heating-bar that is part of the test apparatus. The copper heating-bar can accommodate a number of specimens for simultaneous testing. The vacuum chamber in which the heating bar and other parts of the test apparatus are placed is then sealed and evacuated to a vacuum of at least 7×10^{-3} Pa (5×10^{-5} torr). The heating bar is used to raise the specimen compartment temperature to 125°C. This causes vapor from the heated specimen to stream from the hole in the specimen compartment. A portion of the vapor passes into a collector chamber in which some vapor condenses on a previously-weighed and independently temperature-controlled, chromium-plated collector plate that is maintained at 25°C. Each specimen compartment has a corresponding collector chamber that is isolated from the others by a compartmented separator plate to prevent cross contamination. After 24 h, the test apparatus is cooled and the vacuum chamber is repressurized with a dry, inert gas. The specimen and the collector plates are weighed. From these results and the specimen mass determined prior to the vacuum exposure, the percentage TML and percentage CVCM are obtained. Normally, the reported values are an average of the percentages obtained from three samples of the same material.

NOTE 2—It is also possible to conduct infrared and other analytical tests on the condensates in conjunction with mass-loss tests. Sodium chloride flats may be used for infrared analysis. These flats are nominally 24 mm (1 in.) in diameter by 3.2-mm (0.125-in.) thick, and are supported edgewise in a metal holder that fits into the collector plate receptacle. On completion of the test, the flats are placed into an infrared salt flat holder for examination by an infrared spectrophotometer. As an alternative method, the condensate may be dissolved from the metallic collector, the solvent evaporated, and the residue deposited on a salt flat for infrared tests. Sodium chloride flats shall not be used for CVCM determinations.

4.3 After the specimen has been weighed to determine the TML, the WVR can be determined, if desired, as follows: the specimen is stored for 24 h at 23°C and 50 % relative humidity to permit sorption of water vapor. The specimen mass after this exposure is determined. From these results and the specimen mass determined after vacuum exposure, the percentage WVR is obtained.

4.4 Two or three empty specimen chambers in the heater bar and collector plates on the cold bar, selected for each test at random, can be used as controls to ensure that uniform cleaning procedures have been followed after each test.

4.5 A typical test apparatus can have 24 specimen chambers with 24 associated collector plates so that a number of specimens of different types can be tested each time the foregoing operations are conducted. Three specimen compartments can serve as controls and three can be used for each type of material being tested. The total time required for specimens requiring no prior preparation is approximately 4 days. The equipment should be calibrated at least once a year by using previously tested materials as test specimens.

4.6 The apparatus may be oriented in any direction as long as the configuration shown in Fig. 1 is maintained and bulk material does not fall from the sample holder nor obstruct the gas-exit hole. The dimensions for critical components given in Fig. 2 and Table 1 are provided so that apparatus constructed for the purpose of this test may provide uniform and comparable results.

5. Significance and Use

5.1 This test method evaluates, under carefully controlled conditions, the changes in the mass of a test specimen on

U568C

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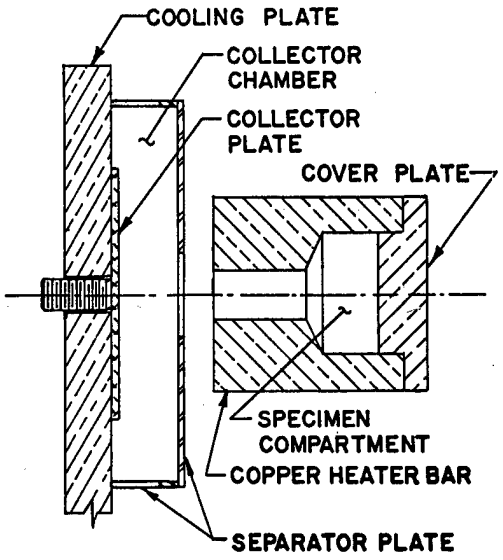

FIG. 1 Schematic of Critical Portion of Test Apparatus (Section A-A of Figure 2)

exposure under vacuum to a temperature of 125°C and the mass of those products that leave the specimen and condense on a collector at a temperature of 25°C.

5.2 Comparisons of material outgassing properties are valid at 125°C sample temperature and 25°C collector temperature only. Samples tested at other temperatures may be compared only with other materials which were tested at that same temperature.

5.3 The measurements of the collected volatile condensable material are also comparable and valid only for similar collector geometry and surfaces at 25°C. Samples have been tested at sample temperatures from 50°C to 230°C, and at collector temperatures from 1°C to 30°C by this test technique. Data taken at non-standard conditions must be clearly identified and should not be compared with samples tested at 125°C sample temperature and 25°C collector temperature.

5.4 The simulation of the vacuum of space in this test method does not require that the pressure be as low as that encountered in interplanetary flight (for example, 10^{-12} Pa (10^{-14} torr)). It is sufficient that the pressure be low enough that the mean free path of gas molecules be long in comparison to chamber dimensions.

5.5 This method of screening materials is considered a conservative one. It is possible that a few materials will have acceptable properties at the intended use temperature but will be eliminated because their properties are not satisfactory at the test temperature of 125°C. Also, materials that condense only below 25°C are not detected. The user may designate additional tests to qualify materials for a specific application.

5.6 The determinations of TML and WVR are affected by the capacity of the material to gain or lose water vapor. Therefore, the weighings must be accomplished under controlled conditions of 23°C and 50 % relative humidity.

5.7 Alternatively, all specimens may be put into open glass vials during the 24-h temperature and humidity conditioning. The vials must be capped prior to removal from the conditioning chamber. Each specimen must be weighed within 2 min after opening the vial to minimize the loss or absorption of water vapor while exposed to an uncontrolled humidity environment. While control of humidity is not necessary at this point, the temperature for the weighing should be controlled at 23°C, the same temperature prescribed for the 24-h storage test.

6. Apparatus

6.1 The apparatus used in the determination of TML and CVCM typically contains two resistance-heated copper bars. Generally, each bar is 650 mm (25.5 in.) in length with a 25-mm (1-in.) square cross section, and contains 12 specimen chambers. The open section of each specimen chamber allows vapors from the specimen to pass through a hole into a collector chamber where it impinges on a removable chromium-plated collector plate maintained at 25°C throughout the test. (See Figs. 1 and 2.) Variations in test apparatus configurations are acceptable if critical dimensions are maintained as prescribed in Table 1.

6.2 Typically, a total of 24 specimen chambers is used for testing during a 24-h vacuum operation; three of the chambers are maintained as controls. The test apparatus can be mounted on the base plate of a vacuum system within a narrow vacuum bell, 260 mm (10¼ in.) in diameter, that rests on a specially adapted feed-through collar, also supported by the base plate.

6.3 The operation of the vacuum chamber system and any device for raising the vacuum bell can be automatically controlled. Power to the heating element mounted in the copper bars is generally controlled by variable transformers through temperature controllers. Recorders with an electronic icepoint reference junction feedback may be used to monitor the heater bar temperatures. A heat exchanger using a suitable fluid may be used to maintain the collector plate at 25°C during the test.[4]

6.4 It is recommended that the vacuum chamber system include automatic controls to prevent damage in the event of power failure or cooling fluid supply failure when in unattended operation. Care must be taken to prevent backstreaming of oil from vacuum or diffusion pumps into the vacuum chamber.

7. Test Specimen

7.1 Finished products (for example, elastomers, hardware, and structural parts) are cut into small pieces on the order of 1.5 to 3.0-mm (1/16 to 1/8-in.) cubes to fit into the specimen boat. Boats approximately 10 by 6 by 12 mm (3/8 by 1/4 by 1/2 in.) have been found satisfactory.

7.2 Products that require compounding are normally mixed in 10-g batches to ensure representative samples. Materials shall be cured as sheets, thin slabs, or thicker sections to simulate application in actual use; then they shall be sectioned in accordance with the foregoing dimensions for specimen cubes.

7.3 Adhesive tapes shall be applied to a surface, such as a preweighed aluminum ring or foil, to simulate actual use. Paints can be applied to aluminum foil by brushing, dipping, or spraying to approximate the as-used thickness, then cured before testing. A paint can also be cured on an inert surface such as TFE-fluorocarbon, removed as a film, and treated as bulk material. Some adhesives or sealants may be applied to

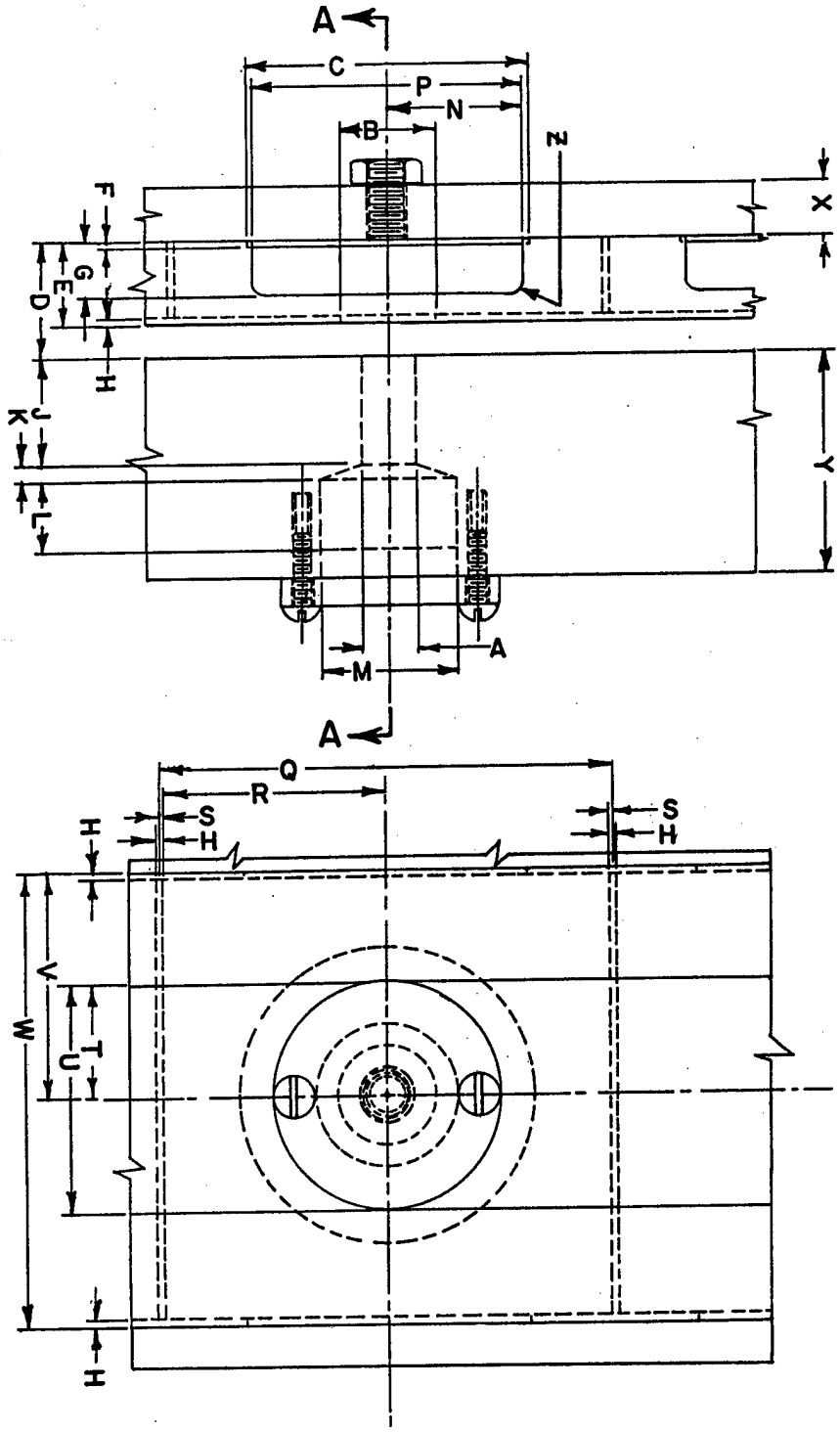

FIG. 2 Critical Portion of Test Apparatus (See Table 1 for Dimensions)

preweighed aluminum foil and cured.

7.4 Greases shall be placed into a boat. Liquids shall be placed directly in a boat or absorbed in an ignited neutral filler such as asbestos or silica and then placed in a boat. The technique used shall be stated in the report. Liquids and greases, especially silicones, are prone to creep; if the material exhibits creep to such an extent that some flows out of the boat, the test results shall be disregarded.

7.5 Minimum specimen masses in the order of 200 mg are required. If smaller quantities are utilized, the accuracy of the measurements may be impaired.

7.6 It is absolutely essential that specimen materials not be contaminated at any step in the specimen fabrication process. Most importantly, specimen material shall not be handled with the bare hands as oils from human skin are

volatile and condensable and thus will cause false TML and CVCM results.

7.7 The following specimen handling procedures are recommended to control contamination:

7.7.1 Wear suitable gloves or finger cots during all specimen preparation steps.

7.7.2 All previously prepared materials can be assumed to be contaminated in the "as-received" condition; and must be cleaned.

7.7.3 Use cleaning solvents that are known to be nonreactive with the specimen material and that are known to leave no residue.

7.7.4 When possible, discard exterior surfaces of materials when preparing specimens. A clean razor blade can be used to shave off exterior surfaces of rubbers, foams, and other soft materials. Exterior surfaces of harder materials can be removed with a clean jewelers' saw. A clean jewelers' drill can be used to remove specimen material from the center part of material suspected of being contaminated.

8. Procedure

8.1 Weigh a prepared aluminum foil boat and return it to its storage beaker in a glass desiccator utilizing silica gel desiccant.

8.2 Weigh a prepared collector and mount it into its cooling-plate receptacle.

8.3 Add the test specimen (100 to 300 mg) to the boat and condition the sample at 50 % relative humidity and 23°C for a minimum of 24 h.

8.4 Weigh the conditioned specimen (see 4.6) using a balance having ±1 μg sensitivity.

8.5 Place the specimen and boat into a specimen compartment of the heating bar in the microvolatile condensable system.[4]

NOTE 2—Prior to the operation noted in 8.5, the copper compartment bar, separator, and cooling plate shall be clean, in position, and awaiting the specimen boats and collector plates.

8.6 Mount and screw down the respective cover plates onto the entry end of each specimen compartment.

8.7 Close the vacuum system and evacuate it to 7×10^{-3} Pa (5×10^{-5} torr) or less within 1 h, using proper operating procedures.

8.8 Control of the collector plate temperature at 25°C (or other temperature if a non-standard test is being conducted) shall be achieved within the first hour of pump-down.

8.9 When a pressure of 7×10^{-3} Pa (5×10^{-5} torr) is reached, turn on the heater bar and adjust the variable transformers to raise the heater bar temperature to 125°C (or other nonstandard test temperature) within 60 min. If the sample temperature will exceed 150°C, up to 2 h may be required to reach temperature. Temperature controllers should maintain bar temperatures at 125°C (or other desired temperature).

8.10 Maintain the collector plate temperatures at 25°C (or other nonstandard temperature).

8.11 Maintain the heater bar temperature at 125°C (or other nonstandard temperature) for 24 h, then close the high vacuum valve to the pumping system and turn off the heater bar current.

8.12 Open the vent valve and backfill with clean, dry nitrogen regulated within a gage pressure range from 10 to 30 kPa (2 to 4 psi) above atmosphere to cool the bars rapidly.

8.13 Allow the heater bar to cool sufficiently to permit handling (nominally 2 h to reach 50°C). Then turn off the collector-plate heat exchangers, return the vacuum chamber to room pressure using the clean, dry nitrogen, and open the chamber.

8.14 Store aluminum boats with specimens and respective collector plates in desiccators (using active silica gel desiccant) immediately. After specimens have cooled to approximately room temperature, but no longer than ½ h, remove and weigh each specimen within 2 min of its removal from the desiccators. Control collector plates are used to detect cross contamination or poor technique. Mass loss of greater than 20 μg by a control is usually due to poor preparation and cleaning of the collector plate. Mass gain of greater than 50 μg is an indication of poor cleaning, poor bake-out of the heater assembly, cross contamination, or poor vacuum technique. Any change of 50 μg (0.05 % of a 100-mg control mass) or greater is reason for concern and for a review of or change in techniques. All data acquired during runs when this occurs shall be discarded or retained with a note indicating the discrepancy.

8.15 Return the foregoing samples to the relative humidity chamber for 24 h if the WVR is to be determined. Weigh the conditioned specimens (see 5.6).

NOTE 3—Annex A1 contains recommended cleaning and storage procedures.

9. Calculation

9.1 Calculate TML as follows:

	Initial Mass, g	Final Mass, g
Specimen and boat	$S_I + B_I$	$S_F + B_I$
Boat	B_I	B_I
Specimen alone	$(S_I + B_I) - B_I = S_I$	$(S_F + B_I) - B_I = S_F$
Difference or mass loss	$L = S_I - S_F$	
	$L/S_I \times 100 = \%$ TML	
Specimen on aluminum foil and boat	$S_I + Al_I + B_I$	$S_F + Al_I + B_I$
Aluminum foil and boat	$Al_I + B_I$	$Al_I + B_I$
Specimen alone	$(S_I + Al_I + B_I) - (Al_I + B_I) = S_I$	$(S_F + Al_I + B_I) - (Al_I + B_I) = S_F$
Difference or mass loss	$L = S_I - S_F$	
	$L/S_I \times 100 = \%$ TML	

9.1.1 A correction may be made using control boats when calculating TML. This correction is recommended but not required unless an excessive mass change occurs as described in 8.14.

9.2 Calculate CVCM as follows:

$$\left(\frac{C_O}{S_I}\right) \times 100 = \% \text{ CVCM} \quad (1)$$

where:

C_O = mass of condensables, g = $C_F - C_I$,
C_I = initial mass of collector plate, g,
C_F = final mass of collector plate and condensables, g, and
S_I = initial specimen mass, g.

9.2.1 A correction may be made using control collector plates when calculating CVCM. This correction is recommended but not required unless an excessive mass change occurs as described in 8.14.

$$C_S = C_{CF} - C_{CI} \quad (2)$$

where:
C_S = change in mass of control collector plate, g
C_{CF} = final mass of control collector plate, g, and
C_{CI} = initial mass of control collector plate, g.

9.3 Calculate WVR as follows:

$$\frac{S_F' - S_F}{S_I} \times 100 = \% \text{ WVR} \quad (3)$$

where:
S_F' = reconditioned mass of specimen and boat after 24 h at 50 % relative humidity, g, and
S_F = final specimen mass, g.

9.4 Calibrate the balance periodically (at least every 6 months) and apply the appropriate calibration factors.

10. Report

10.1 Report the following information:

10.1.1 Trade name and number of the material, the manufacturer, the batch or lot number, or other such identification,

10.1.2 Summary of the preparation schedule (mixing proportions, cure time and temperature, post-cure, cleaning procedures), date prepared,

10.1.3 Number of samples (nominally three for each material, but many organizations use only two samples per test),

10.1.4 Samples configuration (size, shape, etc.). Statement of technique used in handling liquids or greases (see 7.4),

10.1.5 Statement of sample test temperature (125°C), collector plate temperature (25°C), and duration of test and dates of test,

10.1.6 If nonstandard sample or collector temperatures are used, clearly mark the test report NONSTANDARD CONDITIONS, and note the actual test temperature,

10.1.7 Initial mass of conditioned samples, S_I,

10.1.8 Mass of samples as taken from test chamber, S_F,

10.1.9 Final mass of samples after optional reconditioning for 24 h at 50 % relative humidity and 23°C, S_F', if WVR determination is conducted,

10.1.10 Percentage of total mass loss, TML (normally three values for each material and the average value),

10.1.11 Percentage of water vapor regained, WVR (normally three values for each material and the average value), if determined,

10.1.12 Initial mass of the dried collector plates, C_I,

10.1.13 Change in mass of the control collector plate, C_S, in grams,

10.1.14 Final mass of the collectors, C_F,

10.1.15 Percentage of collected volatile condensable material, CVCM (normally three values for each material and the average value),

10.1.16 Infrared spectrum or other analytical description of the condensed contamination when determined, and

10.1.16 Remarks about any noticeable incident or deviation from standard conditions observed during the test.

11. Precision and Bias

11.1 Precision of these measurements was established by interlaboratory tests of 6 materials by 12 organizations. Precision for particular materials is affected by the nature of the material as well as testing variance. For example, monolithic, homogeneous materials with relatively low TML and CVCM values will have high precision and low standard deviation. Materials that are mixed and cured individually before testing may not be homogeneous or completely comparable from organization to organization. Despite such possible variations, the test can successfully identify "good" and "bad" lots of materials, and screen out relatively low outgassing materials from relatively high outgassing materials. For example, Capron film was tested and found to have an average TML value of 3.204 ± 1.136 % for the twelve organizations, and an average CVCM of 0.196 ± 0.0137 % for the 12 organizations. Polyethylene beads had an average TML value of 0.3553 ± 0.0535 % and an average CVCM of 0.0141 ± 0.03117 % for the twelve organizations. Precision for this test method is ±10 % (95 % confidence level) for TML and ±20 % for CVCM.

11.2 Bias for this test method has not been determined.

11.3 Precision of WVR is influenced greatly by whether or not the material is hydrophilic. For example, Capron film WVR was measured by 12 laboratories as 2.510 ± 0.7992 %, or an uncertainty of more 31 %. DC3140 was measured by 12 laboratories as having WVR or 0.02865 ± 0.0279 %, or an uncertainty of almost 100 %. Actual precision of WVR for most materials should be between these extremes. A reasonable approximation is 25 to 30 % uncertainty for materials with WVR of 25 or more, and an uncertainty of 75 to 100 % for materials with WVR of 0.1 % or less. No precision has been estimated for WVR as of yet.

ANNEX

A1. CLEANING AND STORAGE

A1.1 Cleaning

A1.1.1 *General*—The components shall be cleaned after fabrication to remove any residual oils, etc., from the fabrication process. The cleaning operations in A1.1.2 through A1.1.9 shall be performed before each test run unless otherwise specified.

A1.1.2 *Aluminum Boats*—Vapor degrease the boats for 5 or more min. A 1:1:1 by volume chloroform:acetone:ethanol solvent blend has been used successfully for this purpose. Dry the boats at 125 ± 5°C for at least 4 h.

A1.1.3 *Collector Plates*—Immerse and agitate collector plates in the solvent. Follow this with vapor-degreasing for 15 min. A 1:1:1 by volume chloroform:acetone:ethanol solvent blend has been used successfully for this purpose. Dry the collectors for 4 h minimum at 125 ± 5°C.

A1.1.4 *Specimen Chamber and Heating Bar*—Take special care with the bar between test runs to avoid contamina-

tion during subsequent tests. Wash the bar cavities and surface with a suitable solvent. A 1:1 by volume acetone:ethanol solvent blend has been used successfully for this purpose. Mount the bar into the system without specimens. Evacuate the system to 1×10^{-4} Pa (1×10^{-6} torr) and degas the bar at 150° ± 5°C for 4 h minimum. This is 25°C above the normal test temperature. Then turn off the heater to the bar and allow the bar to cool under vacuum. Leave the heater chamber bar in place in the vacuum system. It need only by removed after the test for recleaning. The vacuum system can be configured to close off the bell volume, if necessary, thus permitting the vacuum-pumping system to be off over a weekend.

A1.1.5 *Separator Plate*—Wash the separator plate with a suitable solvent. A 1:1 by volume acetone:ethanol solvent blend has been used successfully for this purpose. Use filtered dry nitrogen gas to remove particulates and to evaporate solvents.

A1.1.6 *Collector Plate Support*—Following the system degassing described in A1.1.4, wipe the collector plate support using a suitable solvent. Ethanol has been used successfully for this purpose.

A1.1.7 *Vacuum Bell*—Poor vacuum is frequently caused by material outgassing from the internal bell surface. Wipe down the bell interior with a suitable solvent as required to restore vacuum-operating efficiency. Ethanol has been used successfully for this purpose.

A1.1.8 *Other Items*—Various other items such as brackets and standoffs can be cleaned as required by wiping with a suitable solvent. A 1:1 by volume acetone:ethanol solvent blend has been used successfully for this purpose.

A1.1.9 *Cleaning Materials*—All wiping materials and swabs shall be preextracted using solvents with which they will be used. (See Note A1.) All solvents shall be of spectro-grade or equivalent purity. The nitrogen gas shall be 99.9 % pure, or better, and shall have a dew point of −60°C (−76°F) or less. The gas shall be filtered using a Molecular Sieve 5A or equivalent. Metal tubing (for example, stainless steel or copper) that is used for gas transfer shall be cleaned before use.

NOTE A1—A recommended extraction procedure for cleaning wiping material is a 24-h treatment in a Soxhlet extractor charged with a mixture of 90 % chloroform:10 % ethyl alcohol.

A1.2 Storage

A1.2.1 *Boats*—After cleaning, the boats can be placed in 5-cm^3 beakers with designated compartment numbers, then stored in a desiccator that contains indicating silica gel. Seal the unit with a low-vapor pressure grease for ground glass joints. The boats shall be weighed within one day of being stored.

A1.2.2 *Collector Plates*—The plates can be mounted on a circular plate rack and stored in a desiccator that contains indicating silica gel. Seal the unit with a low-vapor pressure grease for ground glass joints. Plates shall be weighed within 1 day of being stored.

A1.2.3 *Handling and Storage*—Due to the nature of this method, it is imperative that good cleaning procedures be followed to minimize handling of cleaned parts and the introduction of contaminants after cleaning. Hence, all components that have been cleaned must be stored in such a manner as to maintain their clean state.

A1.2.4 *Vacuum System*—Perform periodic maintenance in accordance with the manufacturer's recommended practices in order to ensure good vacuum system performance.

APPENDIX

(Nonmandatory Information)

X1. TEST REPORTING FORM

X1.1 The following format is suggested for reporting raw data and test results.

OUTGASSING DATA SHEET

Material: (name, part number, lot, etc.)

Description: (material type, sample form, color, etc.)

Condition: (mix and cure, pre or post condition, as received, on substrate, etc.)

Manufacturer:

Requestor: Location: Telephone:

Date: Charge No.:

Blanks: Heater Position No.	( )	( )	( )	
Initial holder mass, g				
Final holder mass, g				
Initial collector mass, g				
Final collector mass, g				
Sample: Heater Position No.	( )	( )	( )	
Initial holder mass, g				
Initial holder plus sample				
Final holder plus sample				
Reweighed sample plus holder, 24 h 50 % RH, g[A]				
Initial collector mass, g				
Final collector mass, g				
Total mass loss (TML) %				Ave. % TML
Total mass gain (CVCM) %				Ave. % CVCM
Total water regained[A]				Ave. % WVR

(Sample WVR)

[A] WVR measurement is optional

Remarks: (Sample appearance, collector appearance after test, any test anomalies, non-standard conditions, problems, etc)

Date test begun:
Sample temperature, °C:
Collector temperature, °C:
Date test completed:
Pressure torr:
Time at test temperature hours:

Operator signature:

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TITLE: **LOS ALAMOS ADVANCED FREE-ELECTRON LASER**

AUTHOR(S): K. C. D. Chan, R. H. Kraus, J. Ledford, K. L. Meier, R. E. Meyer, D. Nguyen, R. L. Sheffield, F. L. Sigler, L. M. Young, T. S. Wang, W. L. Wilson, and R. L. Wood

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ABSTRACT

Los Alamos researchers are building a free-electron laser (FEL) for industrial, medical, and research applications. This FEL, which will incorporate many of the new technologies developed over the last decade, will be compact, robust, and user-friendly. Electrons produced by a photocathode will be accelerated to 20 MeV by a high-brightness accelerator and transported by permanent-magnet quadrupoles and dipoles. The resulting electron beam will have an excellent instantaneous beam quality of 10 π mm mrad in transverse emittance and 0.3% in energy spread at a peak current up to 300 A. Including operation at higher harmonics, the laser wavelength extends from 3.7 μm to 0.4 μm.

INTRODUCTION

The Advanced Free-Electron Laser (AFEL) project is a 5-year program funded internally by Los Alamos National Laboratory. The mission of the project is to advance the state of the art of the free-electron laser (FEL) with a goal to build FELs that are useful for industrial, medical, and research applications. The requirements for such FELs are low cost, compactness, robustness, high reliability, and user-friendliness.

Currently, we are building a FEL to fulfill these requirements using state-of-the-art components now available. The operational experience of such a FEL will help us identify research needed for future improvements in electron sources, wigglers, optical systems,

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diagnostics, and control systems. We will extend the frontiers of these areas in the coming years.

Figure 1 is a floor plan of the AFEL Facility [1]. The floor area is approximately 40 ft by 70 ft. The main areas are the control room, the laser room, and the vault. The control room contains the computer-based control system and the signal-processing equipment; the laser room contains the drive-laser for the photoelectron source and the equipment to analyze the FEL light; and the vault houses the FEL system.

Figure 2 shows the layout of the FEL system. The electron-beam parameters are summarized in Table I. The system consists of five major subsystems: a photoelectron source, a high-brightness linac, an emittance-preserving beamline, a micro-wiggler FEL oscillator, and a computer-based control system.

PHOTOELECTRON SOURCE

A photoelectron source [2] is necessary to achieve the compactness and high beam brightness of the system. It has two major components: a drive laser and a photocathode.

Figure 3 is a schematic of the drive laser. The modelocked Nd:YLF oscillator generates 60-ps-long micropulses at a rate of 108 MHz. These micropulses are compressed to 10 ps, amplified and frequency doubled to 523 nm. The output laser power, averaged over a 1-μs macropulse, is 1 kW.

The photocathode has a CsK_2Sb surface. A container with six photocathodes, called the 6-pack configuration, will be installed. The cathodes will have quantum efficiencies of 5% or better. In fact, with the available drive-laser power, the quantum efficiency required will be > 0.2%. With the 6-pack configuration and high drive-laser power, the effective lifetime of the photoelectron source will be longer than a month.

HIGH-BRIGHTNESS ACCELERATOR

Figure 4 is a schematic of the accelerator. A copper structure, which is installed inside a vacuum vessel, is an on-axis-coupled structure operating at 1300 MHz. It is 1.2 m

long and consists of one half accelerating cell followed by 10 full accelerating cells. The photocathode is installed at the half accelerating cell. The structure is thermally isolated to the vacuum vessel so that it can operate at liquid nitrogen temperature with reduced power loss.

The structure is designed to produce a 20-MeV beam with high brightness. Simulations showed the possibility of instantaneous transverse emittance (normalized and 90%) of better than 10 π mm mrad and the energy spread of better than 0.3%. Special considerations [3] have been taken to achieve these beam qualities. First, the first two and a half accelerating cells are coupled using a four-coupling-slots scheme, so that the asymmetric focusing force caused by coupling slots is minimized. Second, the structure is detuned to have a field of 5 MV/m in the first coupler cell, so that conditions for multipactoring do not exist. Third, the first two and a half cells have a shape slightly different from that of the rest of the accelerating cells, so that the threshold current for regenerative beam breakup is raised above 1 A. Fourth, a high field gradient of 25 MV/m is used in the half accelerating cell, so that electrons can be quickly accelerated and the effects of space-charge force is minimized.

EMITTANCE-PRESERVING BEAMLINE

The beamline (Fig. 5) is designed to preserve the good beam qualities from the linac [4]. It is simple and short. The entire beamline is installed on a 6-ft by 10-ft, vertically-mounted optical table. The electron beam from the linac is matched to the rest of the beamline with two quadrupole doublets. Such a matching section simplifies the operation of the system because the beam dynamics for the rest of the system is separated from the beam dynamics in the accelerator. The beam is then bent by 60° with an achromatic bend consisting of two dipoles and one quadrupole. It traverses a microwiggler and is bent further by a spectrometer towards a beam dump below ground.

Reference 5 describes the alignment requirements of the components along the beamline for preserving the beam quality. To minimize wakefield effects, beampipes 1" in diameters are used throughout the beamline (except at the wiggler) and the electron beam is tightly focused, particularly at the achromatic bend.

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We will use diagnostics that observes optical transition radiations to measure beam positions and emittances [6]. A system of beam position monitors and beam steerers will be installed to provide active beam-position control [7].

We use only permanent-magnet dipoles (Fig. 6) and quadrupoles (Fig. 7) along the beamline. Permanent-magnet transport elements [8] are used because they are compact, simple to operate, and have practically no power and cooling requirements. They are also expected to produce magnetic fields without jitters. Stepper motors will vary the fields in these devices linearly between -10 T/m and 60 T/m for the quadrupoles and between 0.1 T and 0.5 T for the dipoles.

MICROWIGGLER FEL OSCILLATOR

The FEL resonator is 1.4 m long and equipped with 1-in diameter, R=0.696 m mirrors. Either broadband silver mirrors or narrow-band, multilayered dielectric mirrors will be used. During initial operation, a 1-cm-period, permanent-magnet wiggler (Fig.8) operating at the fundamental mode will be used to produce 3.7 μm light. With 24 periods, we expect an efficiency of 2.5%. Later on, an electromagnetic wiggler with forty 0.3-cm periods will be used. When operating at the fifth harmonics, it will generate light at 0.36 μm.

COMPUTER-BASED CONTROL SYSTEM

A computer-based control system has the advantages of minimal staffing, flexibility in reconfiguration, piecemeal implementation, and easy and integrated data access. We are producing the control system for AFEL [9] with the Experimental Physics and Industrial Control System (EPICS) [10] developed at Los Alamos. EPICS provides distributed processing within a high-performance run-time environment and includes a comprehensive set of application development tools. These tools save us considerable time and effort in building the run-time database, operator displays, and sequence programs.

Figure 9 shows the hardware environment of the control system. VME crates and Sun Workstations communicate via the Ethernet. The VME crate is the basic input/output controller. It contains an Allan/Bradley scanner to control the input/output of digital and

analog signals, an IEEE 488 Card to control various commercial equipment, and a stepper-motor controller. Figure 10 shows the software environment, including the development tools. The screen display is designed using the Display Manager and Display Language. The database is constructed and modified with the Database Configuration Tool. Sequence programs to control processes are written in the State Notation Language.

PROGRESS TO DATE

The facility is close to completion. The major components have been designed and are in various stages of fabrication. The linac structure has been tuned and assembled. It will be installed in the vacuum vessel and is scheduled for rf-power operation in November 1991. The fabrication of the dipoles and quadrupoles will be completed early in 1992. We expect to conduct electron-beam and FEL experiments in the spring of 1992.

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Figure Captions

Fig.1. Floor plan of the AFEL Facility.

Fig.2. The FEL system of AFEL.

Fig.3 Schematic of the AFEL drive laser.

Fig.4. Schematic of the AFEL high-brightness accelerator.

Fig.5. Schematic of the emittance-preserving beamline.

Fig.6. Schematics of the permanent-magnet dipole.

Fig.7. Schematic of the permanent-magnet quadrupole doublets.

Fig.8. Schematic of the permanent-magnet microwiggler.

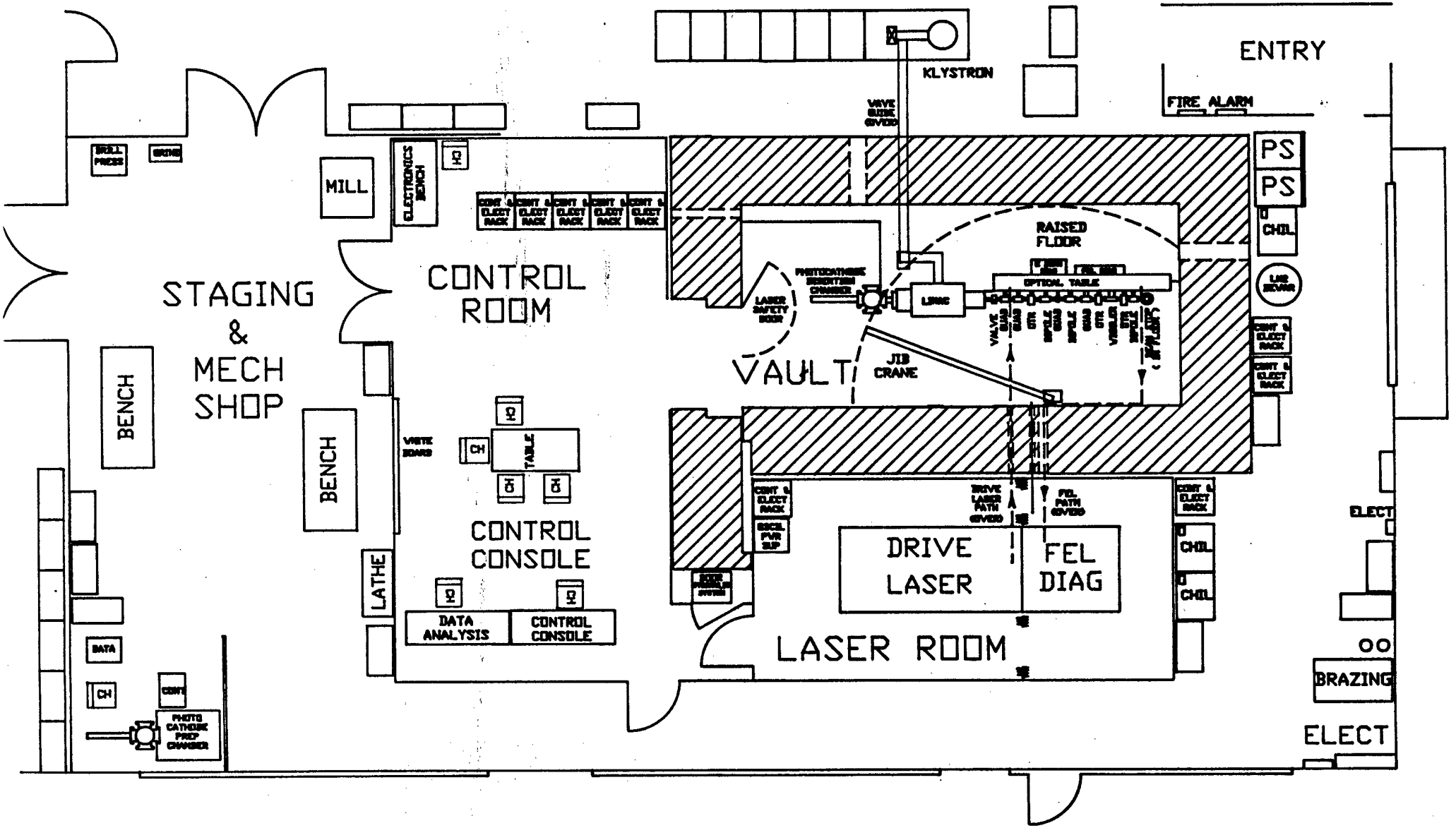
Fig.9. Schematic of the hardware environment of the AFEL control system.

Fig.10. Schematic of the software environment of the AFEL control system.

Table 1
AFEL beam parameters

Charge per micropulse	2.6 (4.6)[a]	nC
Shape of micropulse	Gaussian (square)	
Micropulse length	11.7 (15.4)	ps
Peak micropulse current	220 (310)	A
Micropulse frequency	108	MHz
Average macropulse current	0.28 (0.50)	A
Output energy	20.1	MeV
Macropulse length	10 (50)	μs
Macropulse rate	10 (20)	Hz
Macropulse beam power	5.6 (10.0)	MW
Instantaneous energy spread	< 0.1	%
Instantaneous emittance	< 10	π mm mrad
Micropulse energy spread	< 0.3	%
Micropulse emittance	32 (20)	π mm mrad
Duty factor	10^{-4} (10^{-3})	

a) All numbers in brackets are improved parameters for accelerator operation after initial accelerator turnon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CONTROL ROOM
STAGING & MECH SHOP
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BENCH
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TABLE
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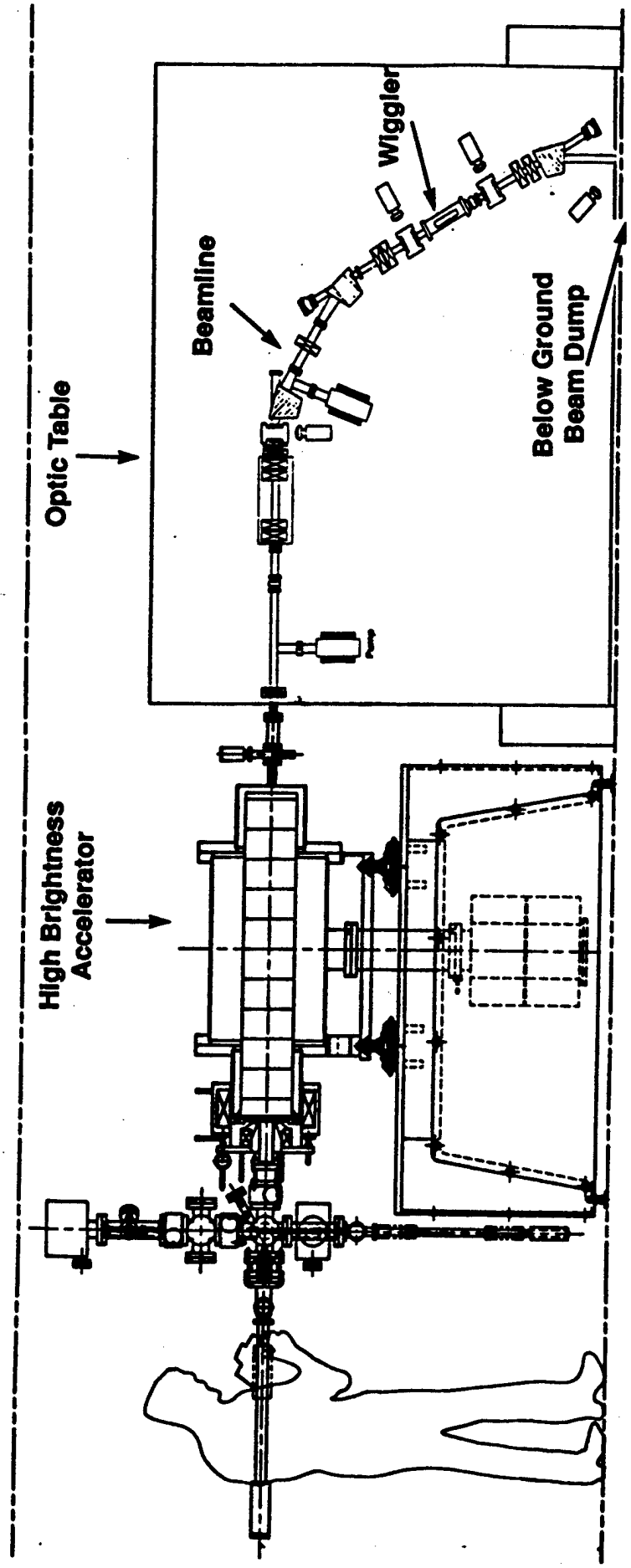
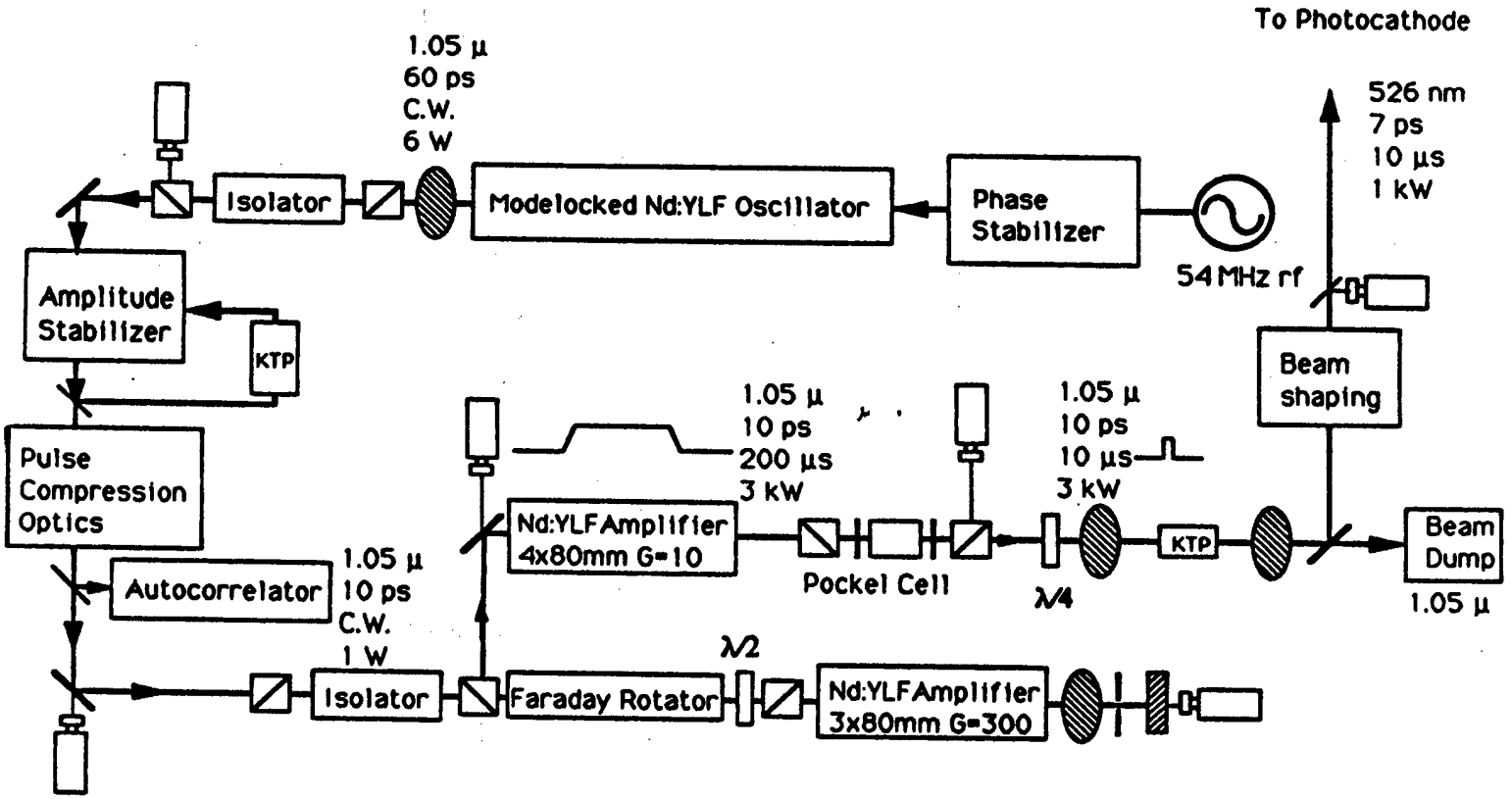

Wiggler
Beamline
Below Ground
Beam Dump
Optic Table
High Brightness
Accelerator


To Photocathode
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1.05 μ
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Pulse Compression Optics
Nd:YLF Amplifier 4x80mm G=10
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Beam Dump
1.05 μ
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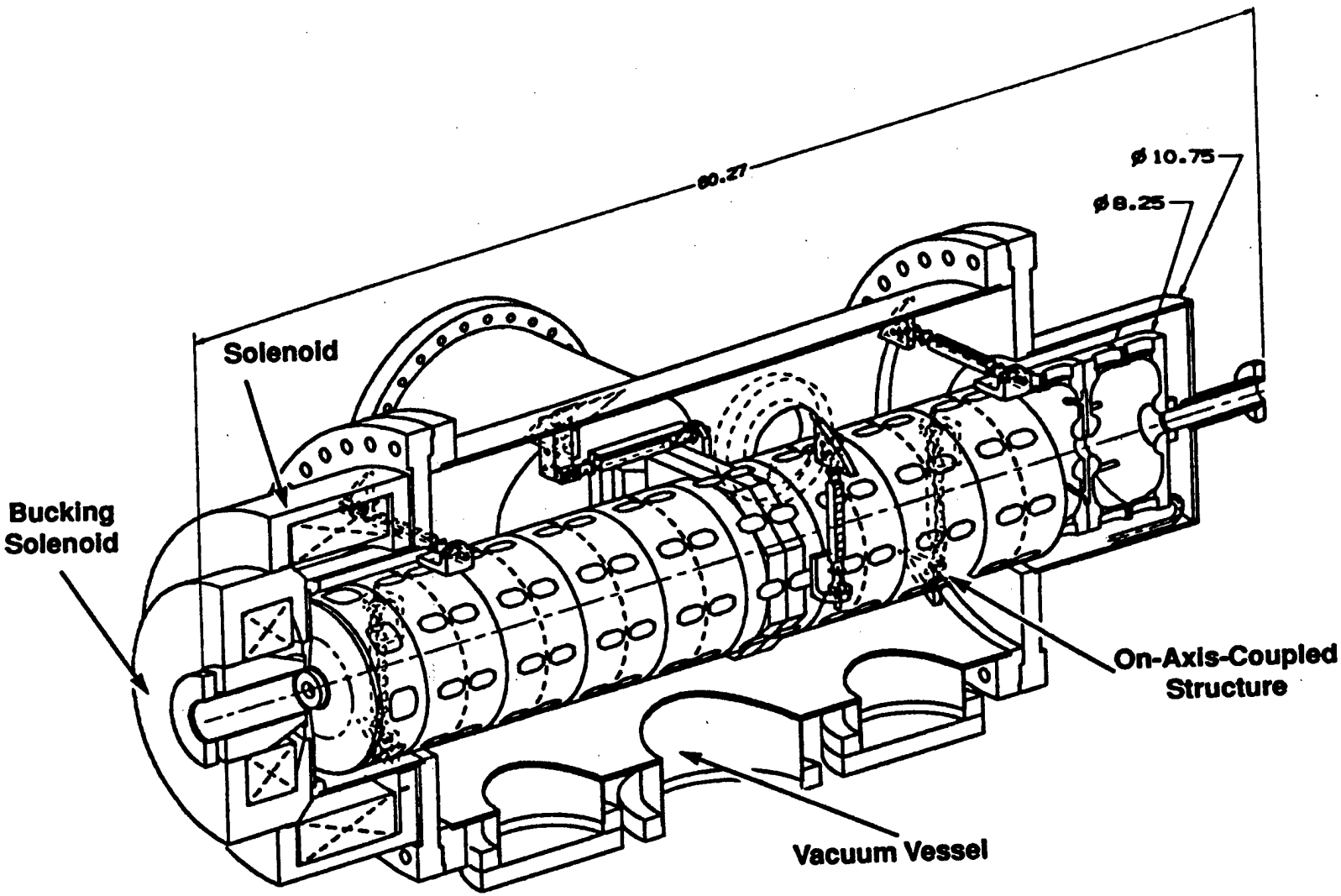
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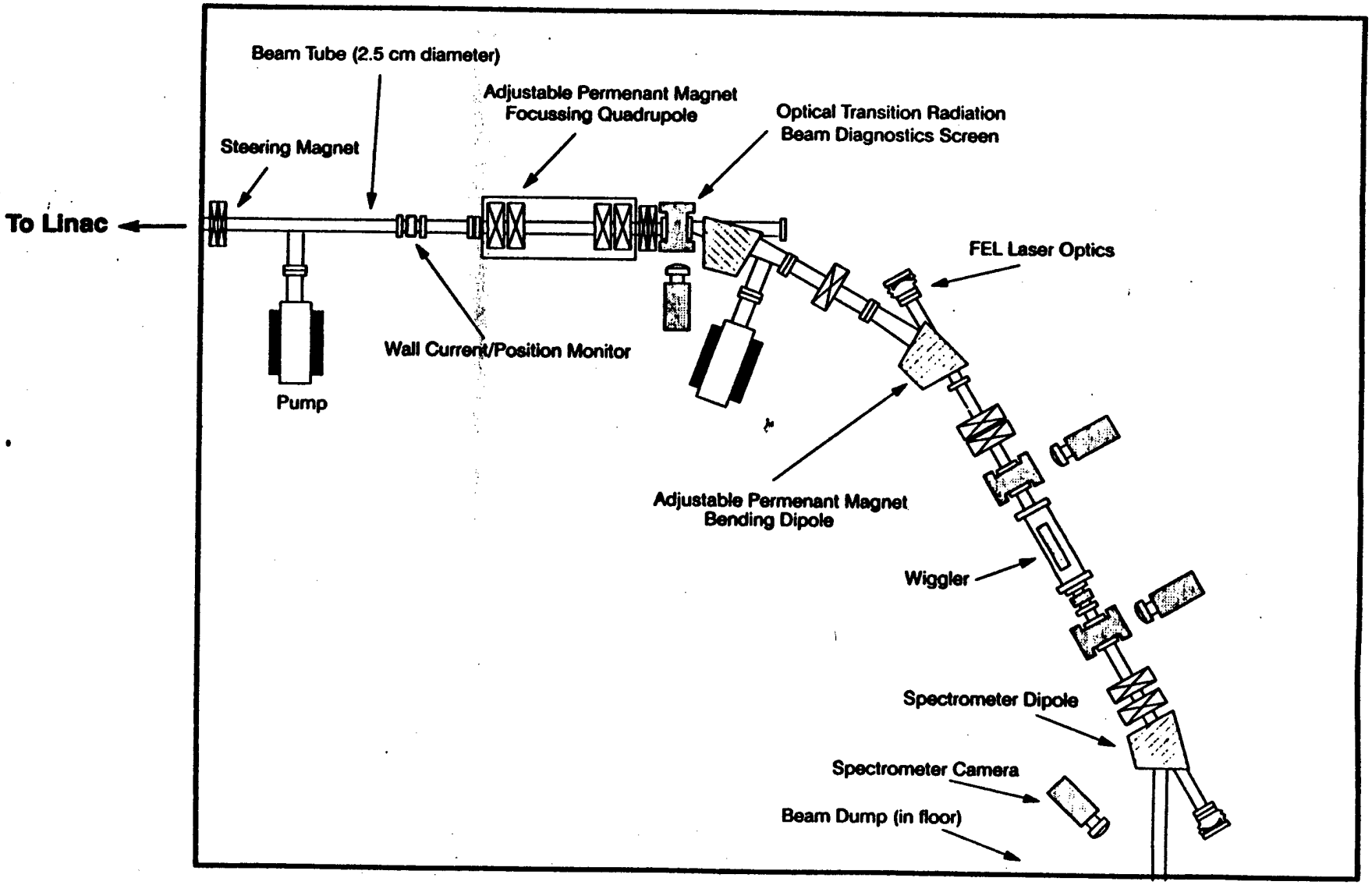
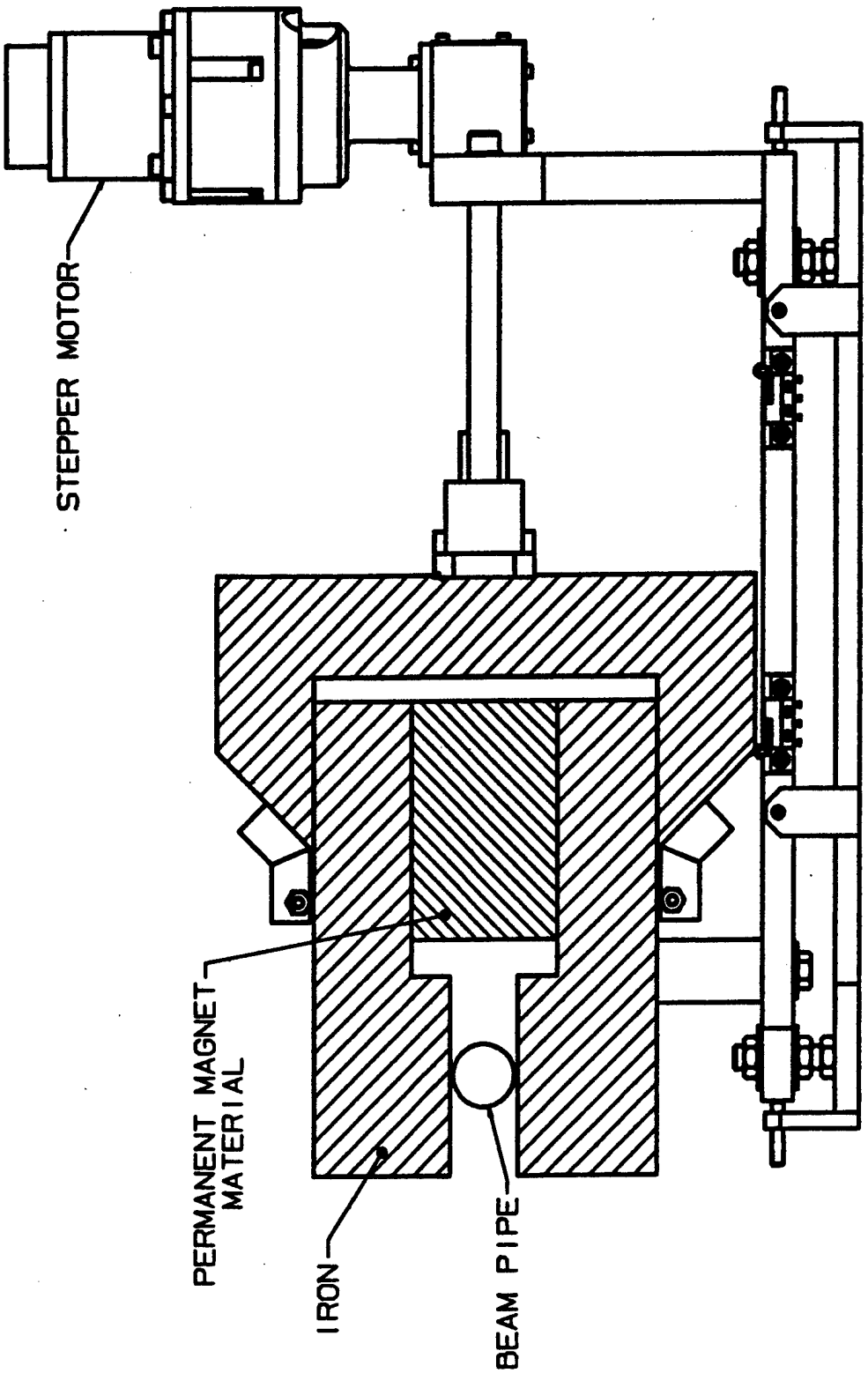

Beam Tube (2.5 cm diameter)
Adjustable Permenant Magnet
Focussing Quadrupole
Optical Transition Radiation
Beam Diagnostics Screen
Steering Magnet
To Linac
FEL Laser Optics
Wall Current/Position Monitor
Pump
Adjustable Permenant Magnet
Bending Dipole
Wiggler
Spectrometer Dipole
Spectrometer Camera
Beam Dump (in floor)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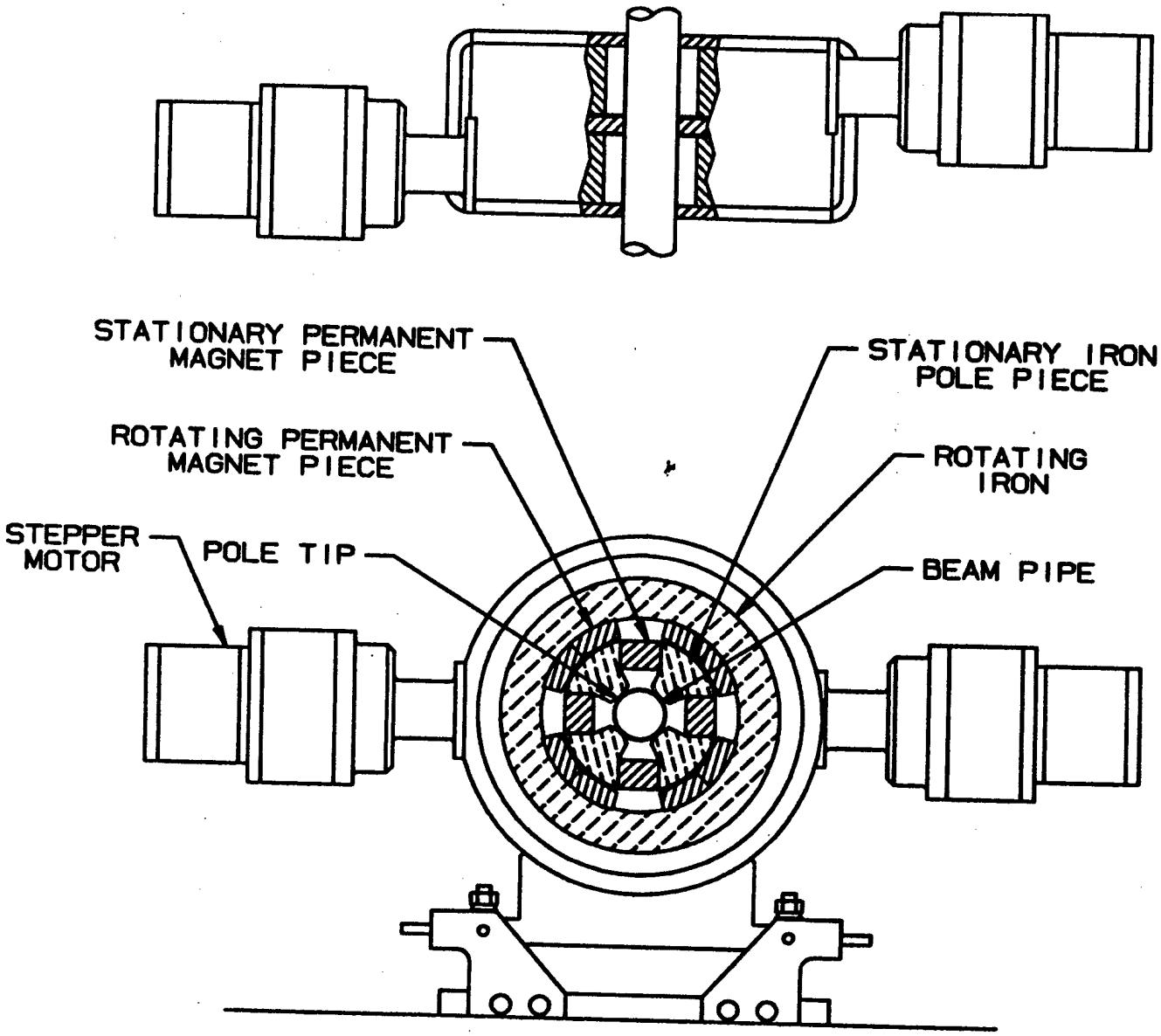
PERMANENT MAGNET MATERIAL
IRON
BEAM PIPE


STATIONARY PERMANENT MAGNET PIECE
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ROTATING PERMANENT MAGNET PIECE
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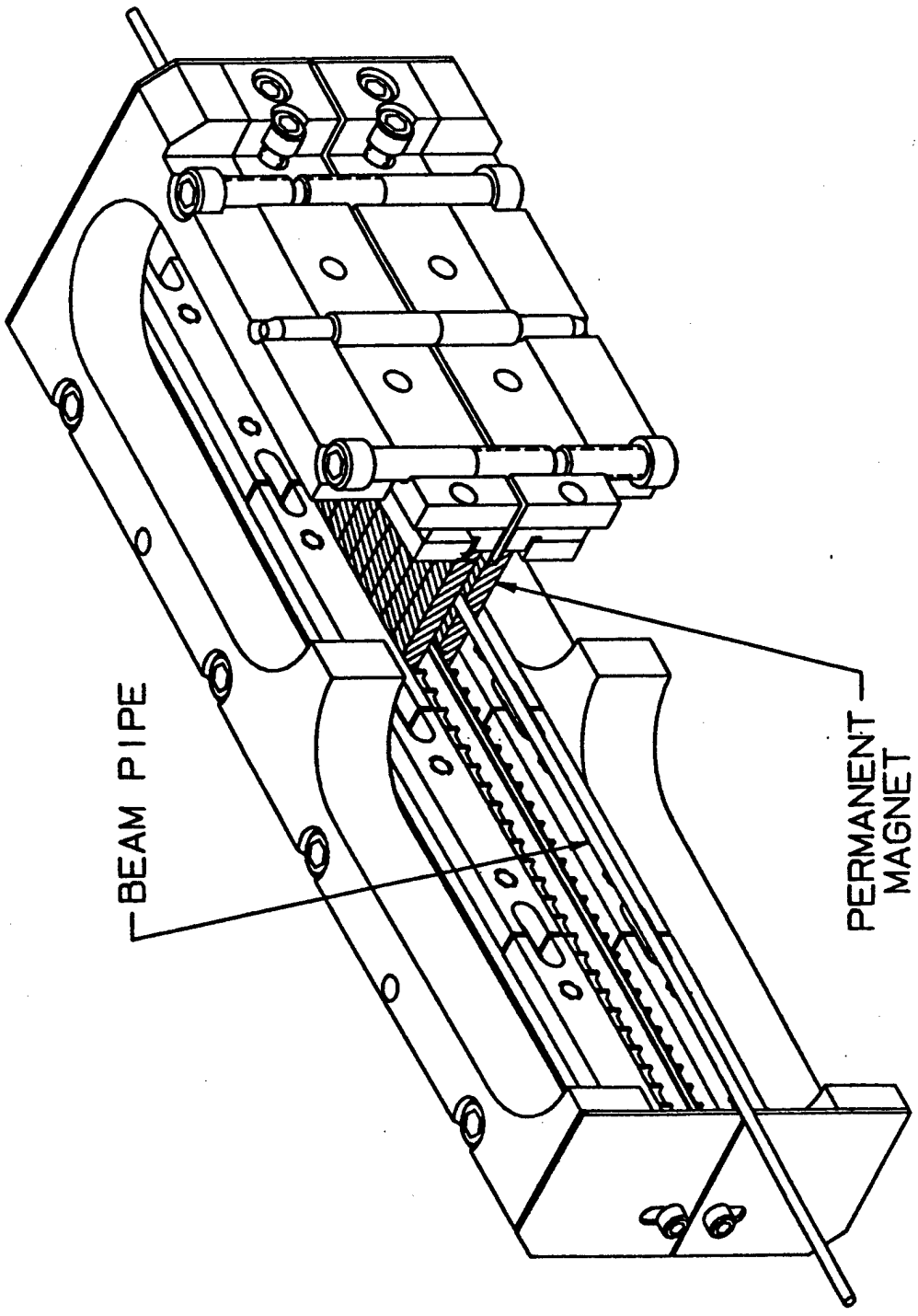
STEPPER MOTOR
POLE TIP
BEAM PIPE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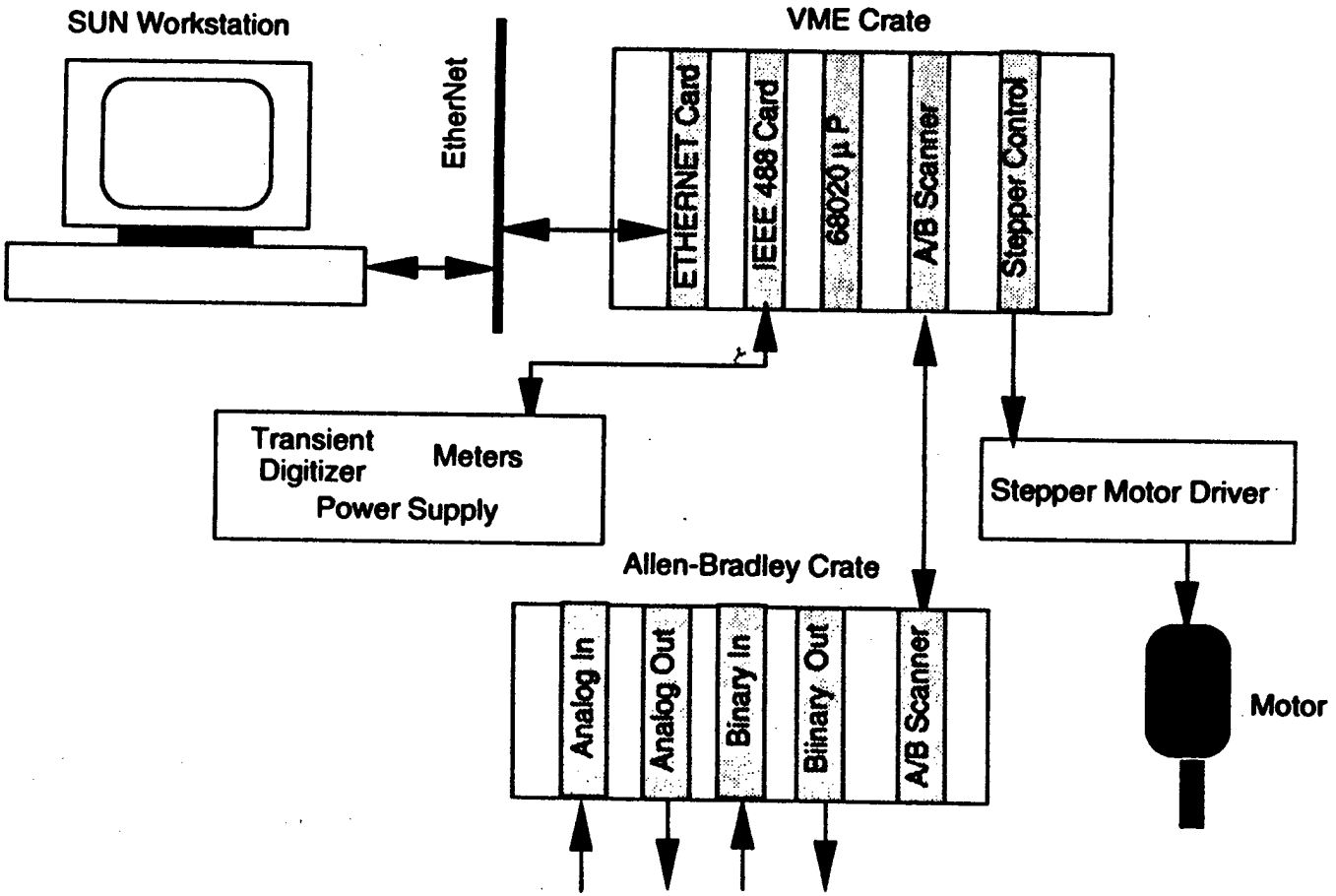
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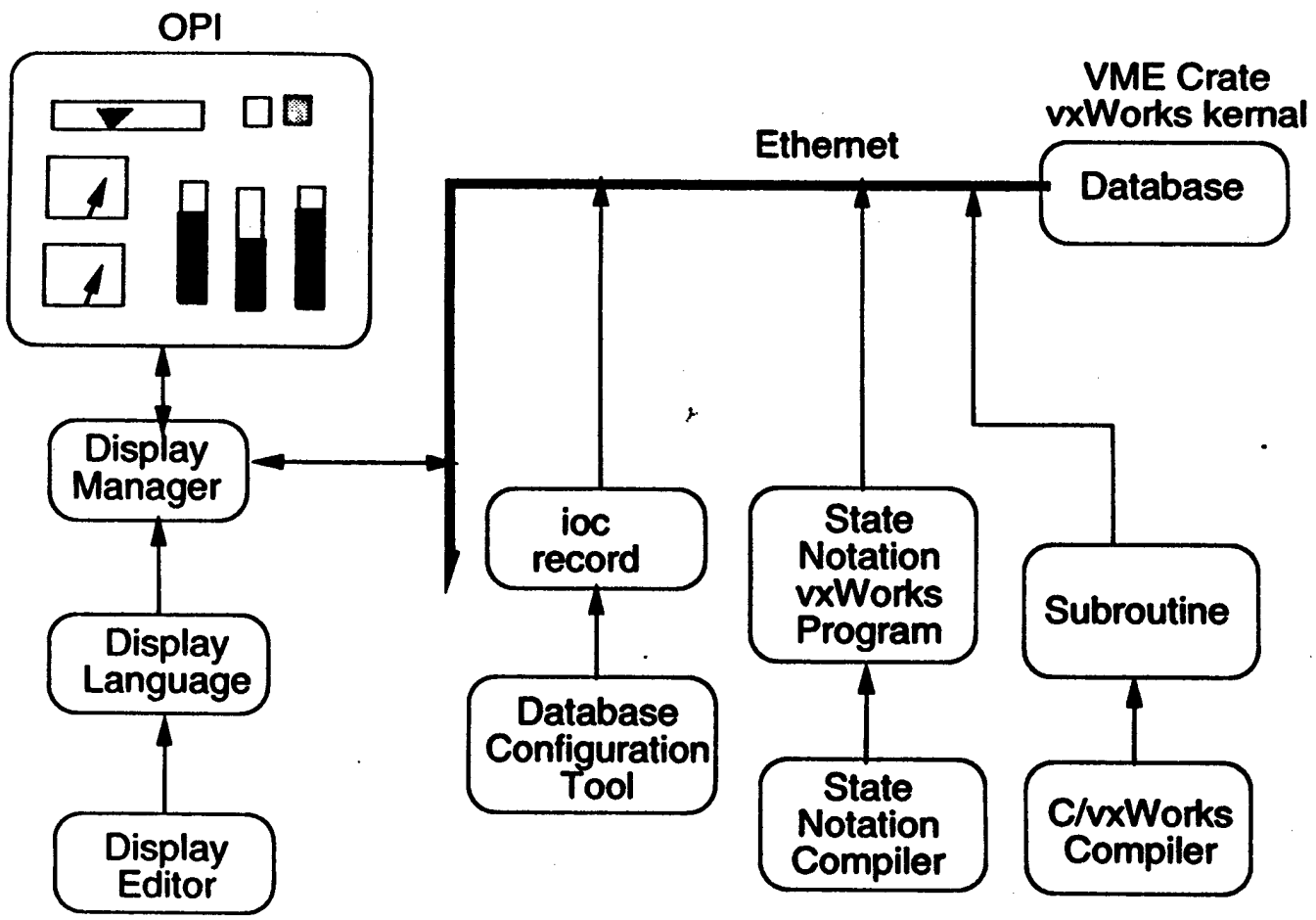
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